TP 5519E

MICROWAVE LANDING SYSTEM
AZIMUTH ANTENNA SUBSYSTEM

by

M. McAloney

M. Senechal

M. Tough

J. Whyte

LE
1985
Canada

Micronav Limited

Sydport Industrial Park

Sydney, Nova Scotia

June 1984

85-6233/

The contents of this report reflect the views of the contractor and not necessarily the official views or policies of the Transportation Development Centre.

PROJECT TEAM

The project team for Micronav Limited was composed of:

Mr. J. Currie

Mr. M. McAloney

Mr. M. Tough

Mr. J. Foote

and others.

REPORT DOCUMENTATION FORM

1. Transport Canada Report No. TP5519E	2. TDC Project No. 4977	3. Recipient's Catalogue No.
4. Title and Subtitle MICROWAVE LANDING SYSTEM AZIMUTH ANTENNA SUBSYSTEM FINAL REPORT		5. Report Date June 1984 6. Performing Organization Report No.
7. Author(s) M. McAloney, M. Senechal, M. Tough, J. Whyte		8. Transport Canada File No. D1455-133-2
9. Performing Organization Name and Address Micronav Limited Sydport Industrial Park P.O. Box 1523 Sydney, Nova Scotia B1P 6R7		10. DSS File No. 07SC. T8200-2-2599 11. DSS or Transport Canada Contract No. OSC.83-00093
12. Sponsoring Agency Name and Address Transportation Development Centre (TDC) 1000 Sherbrooke Street West, Suite 2421 Montreal, Quebec H3A 2R3		13. Type of Report and Period Covered Final May/83-May/84 14. Sponsoring Agency Code 4977
15. Supplementary Notes		16. TDC Project Officer Micha Avni

17. Abstract

This report describes the development and construction of an azimuth antenna for a microwave landing system. A feasibility study demonstrated the use of a fully filled array of 54 slotted waveguide radiators, 4-bit phase shifters and a power divider feed network. Components were fabricated, evaluated and redesigned as required. A prototype azimuth antenna was constructed and extensively tested on an antenna range. The antenna was integrated with control electronics and a microwave source. Ground testing and flight testing of the system confirmed compatibility with standard avionics receiving equipment to international standards.

18. Key Words Azimuth, phased array, waveguide, phase shifters, power divider		19. Distribution Statement A limited number of copies are available from sponsoring agency.	
20. Security Classification (of this report) Unclassified	21. Security Classification (of this page) Unclassified	22. No. of Pages 373	23. Price Nil

TDC/CDT 79-005

FORMULE DE DOCUMENTATION POUR RAPPORT

1. Nº du rapport Transports Canada
TP5519E

2. Nº de l'étude — CDT
4977

3. Nº de catalogue du destinataire

4. Titre et sous-titre
MICROWAVE LANDING SYSTEM AZIMUTH ANTENNA SUBSYSTEM
RAPPORT FINAL

5. Date du rapport
Juin 1984

6. Nº du rapport de l'organisme exécutant

7. Auteur(s)
M. McAloney, M. Senechal, M. Tough, J. Whyte

8. Nº de dossier Transports Canada
D1455-133-2

9. Nom et adresse de l'organisme exécutant
Micronav Limited
Sydport Industrial Park
Case postale 1523
Sydney, Nouvelle Ecosse B1P 6R7

10. Nº de dossier — ASC
07SC.T8200-2-2599

11. Nº de contrat — ASC ou Transports Canada
0SC83-00093

12. Nom et adresse de l'organisme parrain
Centre de développement des transports (CDT)
1000, rue Sherbrooke ouest
Bureau 2421
Montréal (Québec) H3A 2R3

13. Genre de rapport et période visée
Final Mai/83 - Mai/84

14. Code de l'organisme parrain
4977

15. Remarques additionnelles

16. Agent de projet — CDT
Micha Avni

17. Résumé

Ce rapport décrit la mise au point et la construction d'une antenne à balayage azimutal pour système d'atterrissage hyperfréquence (MLS). Une étude a démontré la faisabilité d'un réseau comportant 54 radiateurs en guides d'ondes à fentes, des déphaseurs 4 bits et un réseau d'alimentation à répartiteur de puissance. Les composants ont été fabriqués, évalués et modifiés selon les besoins. Une prototype d'antenne à balayage azimutal a été construit et testé de façon approfondie sur un terrain d'essai. Des circuits de commande et une source hyperfréquence étaient incorporés à l'antenne. Des essais au sol et en vol ont permis de vérifier que le système est conforme aux normes internationales pour le matériel de réception standard utilisé en avionique.

18. Mots-clés
Azimut, réseau à commande de phase, guide d'ondes, déphaseur, répartiteur de puissance

19. Diffusion
Un nombre limité de copies est disponible auprès de l'organisme parrain

20. Classification de sécurité (de ce rapport)
non-classifié

21. Classification de sécurité (de cette page)
non-classifiée

22. Nombre de pages
373

23. Prix
Nil

CDT/TDC 79-005

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the assistance provided by the personnel of Canadian Astronautics Limited, Hughes Aircraft Company, and especially Meyer Associates of Boston, Mass.

SUMMARY

This report describes the development of an antenna subsystem used for azimuth scanning in a Microwave Landing System (MLS). It was carried out by Micronav Limited for the Transportation Development Centre to be used with Micronav's MLS control electronics.

The primary objectives of the program were:

a. Carry out a preliminary design.
b. Demonstrate the feasibility of the proposed design.
c. Develop and construct a MLS Azimuth Antenna Subsystem.
d. Carry out detailed testing in Ottawa, in house at Micronav, and at Sydney Airport, next to a runway.

The purpose of this contract is to establish in Canada MLS expertise which will exploit the enormous potential national and international market.

The Microwave Landing System provides an aircraft with the capability for precision approach and landing through the use of sophisticated microwave and computer technology. The azimuth system, which provides the horizontal coverage, consists of two overall subsystems; the antenna itself and the control electronics.

The antenna system electronically sweeps a narrow beam throughout the coverage area to provide high precision positioning information to approaching aircraft. RF energy is distributed from a single microwave source via a corporate feed or power divider to a series of 54 phase shifters and radiating elements. The phase shifters are digitally controlled by the electronics to determine a specific phase distribution across the face of the array.

A separate waveguide, located near the bottom of the other 54 waveguides, provides monitoring signals permitting on enhanced maintenance capability.

To complete the design of the azimuth antenna to high reliability standards, a number of special considerations were assessed. They include the environmental conditions associated with severe arctic winters and desert sun without **degradation of performance.**

The final design specifications are a compilation of electrical and mechanical standards outlined by the International Civil Aviation Organization (ICAO), Federal Aviation Administration (FAA), and Transport Canada.

TABLE OF CONTENTS

1. INTRODUCTION 1
  1.1 General 1
  1.2 Background 1
2. ANTENNA SYSTEM DESIGN 6
  2.1 General 6
  2.2 System Description 8
  2.3 Specifications 12
  2.4 Predicted Performance 17
  2.5 Design Philosophy 20
3. DESIGN AND ANALYSIS 23
  3.1 General 23
  3.2 Microwave Source 23
  3.3 Power Distribution Network 29
  3.4 Phase Shifter 49
  3.5 The Phased Array 90
  3.6 Electronics 117
4. MECHANICAL DESIGN AND ASSEMBLY 121
  4.1 General 121
  4.2 Antenna Support Frame 122
  4.3 Waveguide Assembly Mounting 124
  4.4 Corporate Feed Mounting 128
  4.5 Phase Shifter Mounting 128
  4.6 Control Electronics Mounting 131
  4.7 Monitor Assembly 132
  4.8 Microwave Source Mounting 135
  4.9 Enclosure and Pedestal 135

5. GROUND INSPECTION TESTS 138
  5.1 General 138
  5.2 Overview 139
  5.3 Test Summary 140
6. FLIGHT INSPECTION TESTS 142
  6.1 General 142
  6.2 Objective 142
  6.3 Results 145
7. EXPERIMENTAL PROCEDURES AND RESULTS OF TOTAL PHASED ARRAY ANTENNA 146
  7.1 Experimental Procedures 146
  7.2 Results 148
  7.3 Azimuth Phase Offset Patterns 149
  7.4 Elevation Patterns at 5030, 5060, 5090 MHz 150
  7.5 Azimuth Patterns for 1° Elevation Increments 151
  7.6 Grating Lobes 151
  7.7 Phase Shifter Failure Test Patterns 152
8. DISCUSSION OF SYSTEM RESULTS 153
9. CONCLUSION 155
APPENDIX 1 Scan Program 1 for selecting beam pointing angle 156
APPENDIX 2 Azimuth Radiation Patterns for 1 Degree from -42° to $+42^{\circ}$ at 5060 MHz 181
APPENDIX 3 Azimuth Scans for phase offsets of 22.5°, 45°, 90° and 180° at 0° azimuth angle for frequencies 5030, 5060, 5090 266

APPENDIX 4 Elevation Scans for 5030, 5060, 5090 MHz for azimuth angle 0° 282

APPENDIX 5 Azimuth Scans for every 1° of elevation angle with azimuth angle 0 degrees 286

APPENDIX 6 Grating Lobes 309

APPENDIX 7 Phase Shifter Failures 312

APPENDIX 8 Corporate Feed Return loss/ Forward loss Measurements 318

APPENDIX 9 Ground Inspection Report 324

APPENDIX 10 Flight Inspection Report 343

LIST OF FIGURES

Figure 1 ILS - MLS Coverage Area Comparison 3
Figure 2 Typical MLS Installations 4
Figure 3 MLS Azimuth Antenna Operation 7
Figure 4 System Block Diagram 9
Figure 5 Vertical Coverage For Azimuth Array 13
Figure 6 Elevation Pattern For Azimuth Antenna 13
Figure 7 Worst Case Azimuth Radiation Pattern 19
Figure 8 Microwave Source Configuration 27
Figure 9 Basic Feed Networks 30
Figure 10 Strip-Line Split-Tee Power Divider 35
Figure 11 Design Equations for Split-Tee Power Divider 35
Figure 12 Modified Split-Tee Power Divider 36
Figure 13 Taylor Distribution Plot 39
Figure 14 Corporate Feed - Right Side 40
Figure 15 Power Dividers K1-K10, K24-K27 42
Figure 16 Power Dividers K11-K23 43
Figure 17 Corporate Feed Boards Connection 46
Figure 18 Phase Shifter Block Diagram 52
Figure 19 Types of Phase Shifters 53
Figure 20 Branch Line Hybrid Phase Shifter Bit 55
Figure 21 Equivalent Circuit For Two Branch Coupler, Showing Line and Junction Components 58
Figure 22 Two Branch Coupler and Equivalent Circuit With Junction Components 59
Figure 23 Reflection Type Phase Shifter 59
Figure 24 Reflection Type Phase Shifter Microstrip Design 63

Figure 25 Equivalent Circuit of Reflection Port 63

Figure 26 Reflection Port Phase Versus Length of Microstrip Line 67

Figure 27 Forward Biased Diode Resistance Model 71

Figure 28 Reverse Bias Pin Equivalent Circuit 73

Figure 29 Microstrip Cross Section 77

Figure 30 Board Production Process 80

Figure 31 Hybrid Bit 83

Figure 32 4-Bit Phase Shifter 85

Figure 33 Azimuth Horizontal Coverage 91

Figure 34 Azimuth Vertical Coverage 91

Figure 35 Azimuth Antenna Pattern 97

Figure 36 Required Elevation Plane Radiation Pattern 99

Figure 37 Synthesized Radiation Pattern 101

Figure 38 Edge Slot in Rectangular Waveguide 102

Figure 39 Incremental and Single-Slot Conductance 102

Figure 40 Variation of Slot Admittance With Depth of Cut 102

Figure 41 Slotted Waveguide 104

Figure 42 Coax to Waveguide Assembly 106

Figure 43 Surface Current Distribution For Rectangular Waveguide Propogating TE_{10} Mode 111

Figure 44 Waveguide Slot Length vs. Coupling 112

Figure 45 Monitor Waveguide 115

Figure 46 Antenna Support Structure 123

Figure 47 Waveguide Mounting 126

Figure 48 Phase Shifter Mounting 127

Figure 49 Waveguide Assembly 129

Figure 50 Corporate Feed and Electronics Driver Location 130

Figure 51 Monitor Waveguide Assembly Location 133

Figure 52 Monitor Connector Location 134

LIST OF TABLES

Table 1 Phase and Amplitude Accuracy 18

Table 2 Power Amplifier Specification 25

Table 3 Microwave Excitor Specification 26

Table 4 Corporate Feed Distribution 38

Table 5 Split-Tee Power Divider Design Values 41

Table 6 Phase Shifter Specification 50

Table 7 MA - 4P303 Diode Specification 75

Table 8 Phase Shifter Final Specification and Test Results 87

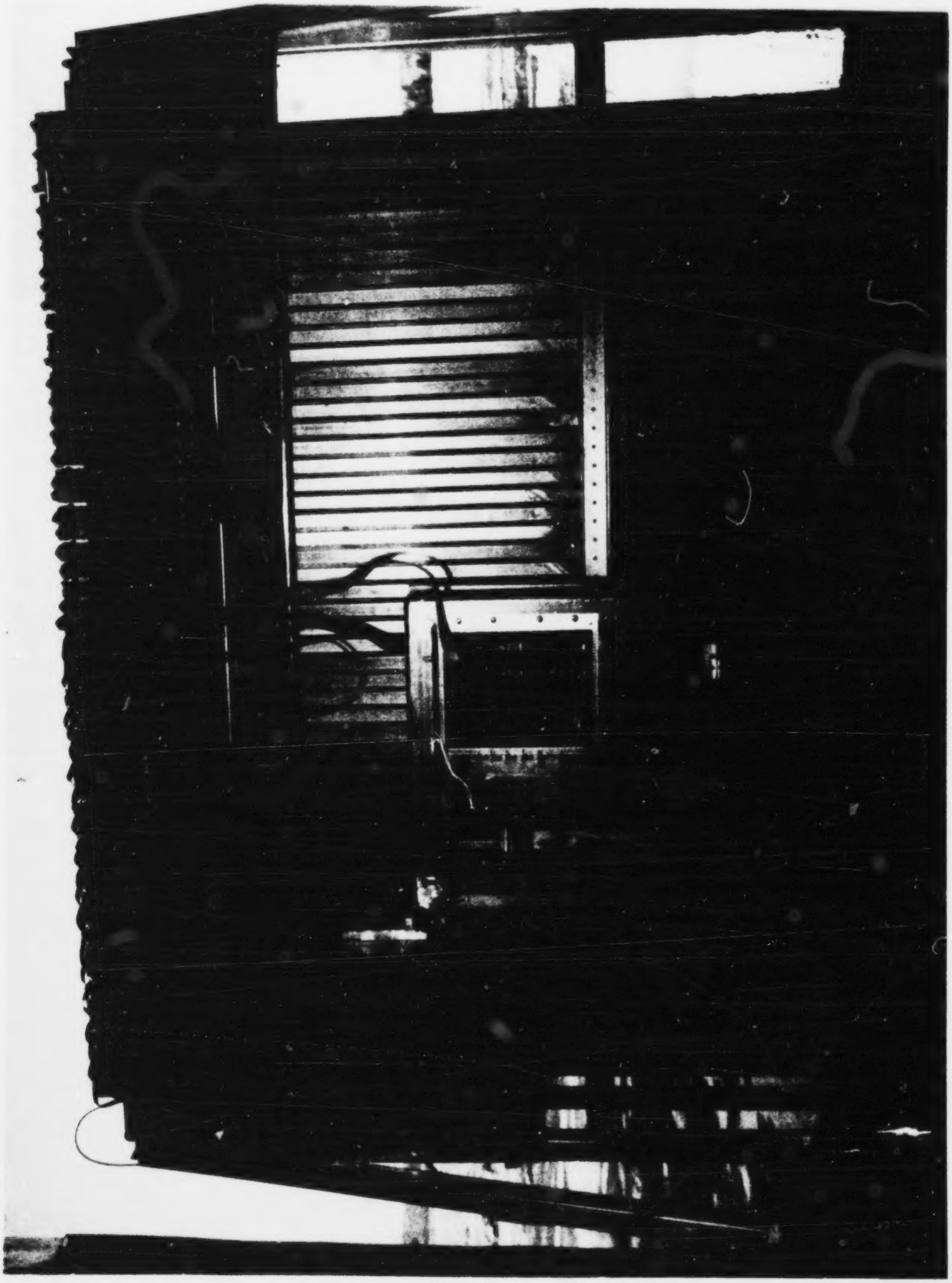
Table 9 Azimuth Amplitude Values 96

Table 10 Monitor Coupling Dimensions 113

Table 11 Monitor Distribution (Freq. 5.060 GHz) 116

Table 12 Summary Sheet of Ground Inspection Tests 141

Table 13 Flight Test Summary 144



MLS Azimuth Antenna System with Control Electronics (Rear View)

1. INTRODUCTION

1.1 General

In May of 1983, the Transportation Development Centre contracted Micronav Limited to develop and construct a microwave landing system azimuth antenna. This subsystem is to be used in conjuction with the control microelectronics previously designed.

With the successful completion of the azimuth antenna, a major milestone has been reached in the design of an all Canadian MLS.

1.2 Background

The purpose in using a landing system is to provide the personnel of an aircraft, preparing to land, guidance information relating the airplane's position to that of the runway and desired glide path. At present, instrument landing system (ILS), developed during World War II, is used. It uses two fixed radio beacons, which originate from large antennas located near the runway. A receiver installed in an aircraft cockpit receives these radiated beams, deriving fly left or right and angle of descent information. Instrument landing systems are limited in that only one approach path is provided regardless of aircraft type or other criteria. They are expensive to install, dependent on site terrain, and offer only 40 separate channels.

The microwave landing system (MLS) has been selected by the International Civil Aviation Organization (ICAO) as the world wide standard for aircraft landing guidance. Under the ICAO plan, Instrument Landing Systems will be replaced by MLS over a period of 10 years commencing in 1985.

The MLS has several inherent advantages that make it the system of the future, thereby forcing ILS into retirement. They are:

a. Improved performance and precision.

b. Ability to serve new locations such as mountainous areas and oil rigs.

c. Improved safety.

d. Multiple approach paths for helicopters, normal, and STOL fixed wing aircraft.

e. 200 channels available.

f. Aircraft fuel savings due to shorter approach routes and reduced stacking.

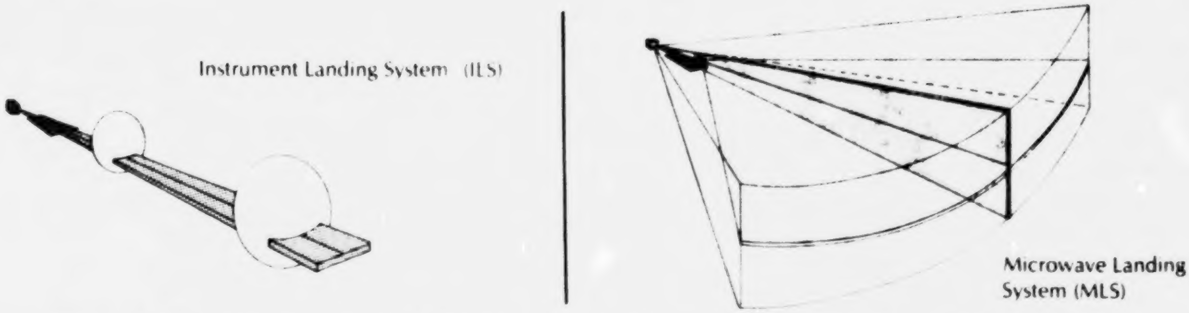
g. Minimal site preparation.

h. Capability of automatic landings.

i. Inexpensive installation.

j. Greatly reduced terrain dependence.

Figure 1 illustrates the ILS versus MLS coverage areas. MLS provides proportional guidance information over ±40 degrees of azimuth angle to all aircraft within 20 nautical miles of the installation. The typical installation as shown in Figure 2 consists of azimuth and elevation installations as well as Distance Measuring Equipment (DME). Together they can provide a variety of aircraft with precision guidance


Instrument Landing System (ILS)
Microwave Landing System (MLS)

ILS provides a single, fixed approach path to the runway which all aircraft, regardless of flight characteristics, must follow. MLS uses two *scanning beams* — one lateral and one vertical — to provide a variety of approach paths for different aircraft types, from airline jets through STOL aircraft to helicopters.

Figure 1 ILS - MLS Coverage Area Comparison

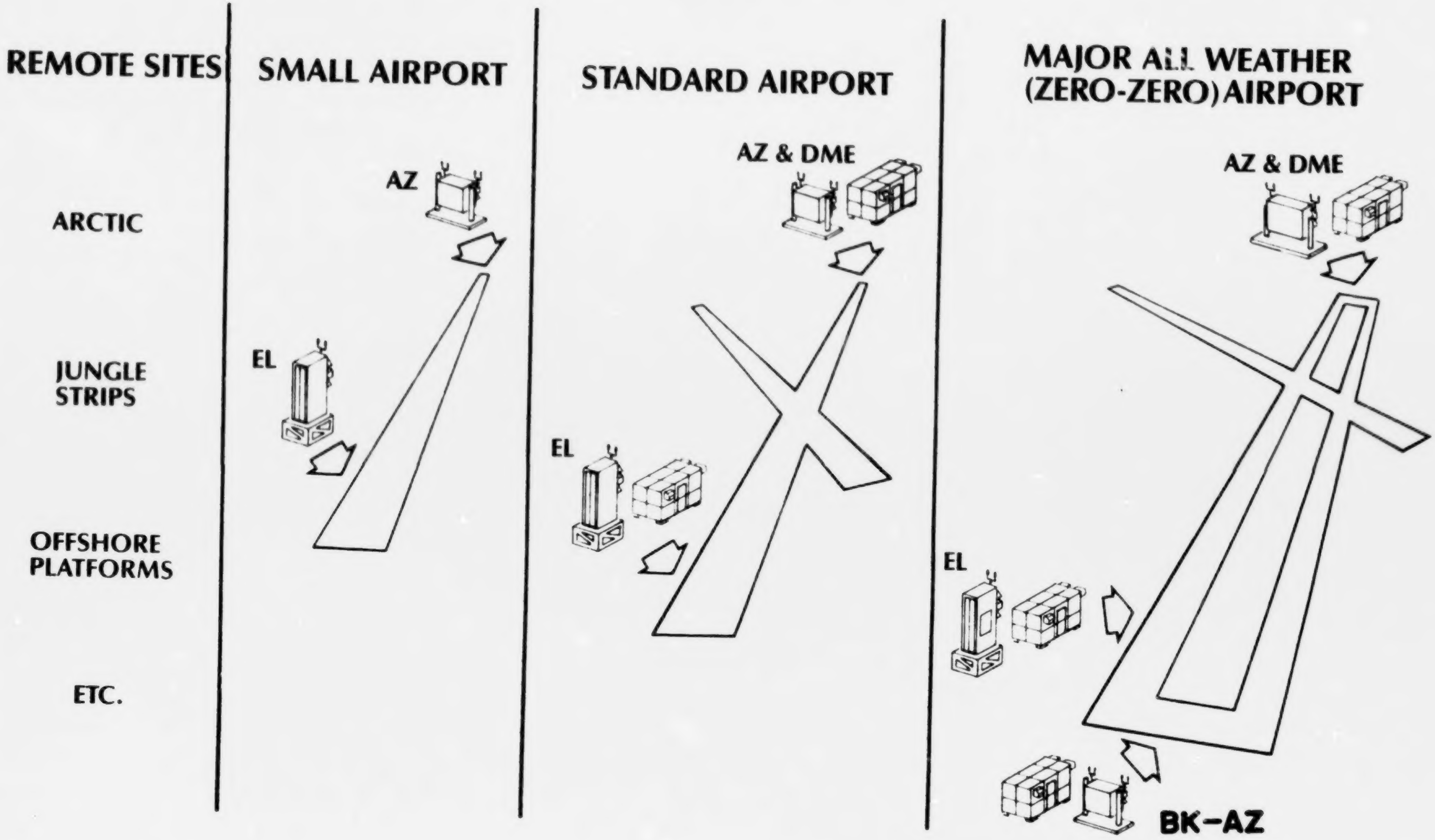

REMOTE SITES
ARCTIC
JUNGLE STRIPS
OFFSHORE PLATFORMS
ETC.
SMALL AIRPORT
AZ
EL
STANDARD AIRPORT
AZ & DME
EL
MAJOR ALL WEATHER (ZERO-ZERO) AIRPORT
AZ & DME
EL
BK–AZ

Figure 2   Typical MLS Installations

information at locations ranging from remote arctic airstrips to major international airports.

Transmission of the MLS azimuth and elevation signals occurs in the C band frequency range (approximately 5 GHz) drastically reducing ground effects seen with ILS installations. The MLS receiver, due to the Time Reference Scanning Beam (TRSB) technique used in MLS, has the ability to recognize and reject unwanted reflected signals arriving out of the proper sequence. Because of these characteristics, the signals are not only extremely stable, which is vital for zero visibility operations, but can be used in mountainous and other locations where ILS would be unflyable.

The contractor for this project, Micronav Limited, was incorporated in December 1980 to pursue the development of a microwave landing system. At present, an azimuth system is in operation and an elevation antenna is under development. Subcontracts were given to Hughes Aircraft Company for a preliminary design feasibility study and to Canadian Astronautics Limited for antenna design and construction.

The study, design, and fabrication of the azimuth subsystem make up the contents of this report. The following sections describe in detail the development of individual components, system integration, testing and evaluation. Results of MLS antenna testing, ground testing and flight testing of the MLS are included within this report.

2. ANTENNA SYSTEM DESIGN

2.1 General

Having described the functional nature of MLS as a whole, this section discusses the azimuth scanning subsystem's function and the ensuing design goals and specifications.

The function of the azimuth antenna is to transmit a 2° beam which scans "TO" and "FRO" at a constant rate of 20,000°/sec between coverage limits of ±40° from the runway centerline. A MLS receiver located on board an aircraft measures the length of time between a beam passing in one direction and then returning in the opposite direction. The sweep from left to right with respect to an incoming aircraft is known as the "TO" scan. In the reverse direction, right to left, the sweep is known as the "FRO" scan. Timing commences when the TO scan beam passes the receiver and ends when the FRO scan beam passes the receiver. An aircraft to the right of the runway centerline will receive a long time interval when compared to another flying to the left of the centerline. Figure 3 illustrates the concept of the azimuth TO-FRO sweep.

The time measurement is decoded by the MLS receiver to determine the aircraft's approach angle with respect to the runway. This course is compared with the desired course, selected by the pilot, to give him fly right/fly left information. A pilot can select any approach angle inside the coverage area allowing him to make curved approaches or conventional "straight-in" approaches. MLS which operates on this time difference method is referred to as a Time

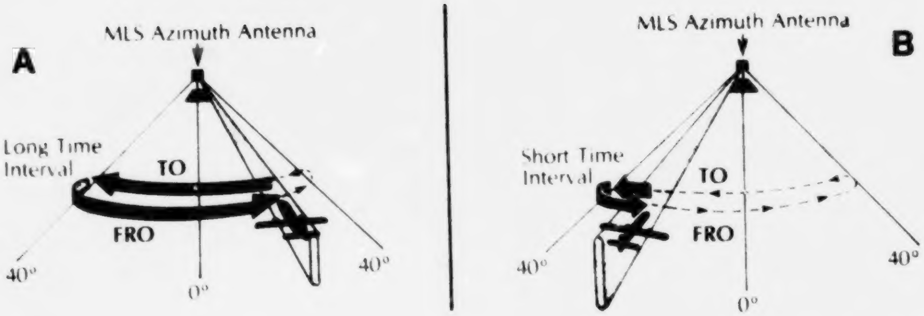

A
MLS Azimuth Antenna
Long Time Interval
TO
FRO
40°
0°
40°
MLS Azimuth Antenna
B
Short Time Interval
TO
FRO
40°
0°
40°

Figure 3 MLS Azimuth Antenna Operation

Referenced Scanning Beam (TRSB) system.

2.2 System Description

To understand the operation of the azimuth system, the basic component blocks of the unit must be considered. Functionally, the azimuth system is composed of eight different sections which are shown in the block diagram in Figure 4. Each is generally addressed below:

a. Microwave Source

The microwave source consists of a power amplifier, exciter, DPSK modulator and four-way switch. It provides 10 watts of RF power on the selected channel in the MLS frequency range.

b. Corporate Feed

The corporate feed divides the microwave energy into 54 outputs and provides the correct amplitude and phase distribution over the entire bandwidth.

c. Phase Shifters

The phase shifters control the phase of the RF energy into the radiating elements. Each of the 54 phase shifters can be set for any $22\frac{1}{2}^\circ$ phase increment making possible scanning of the main beam.

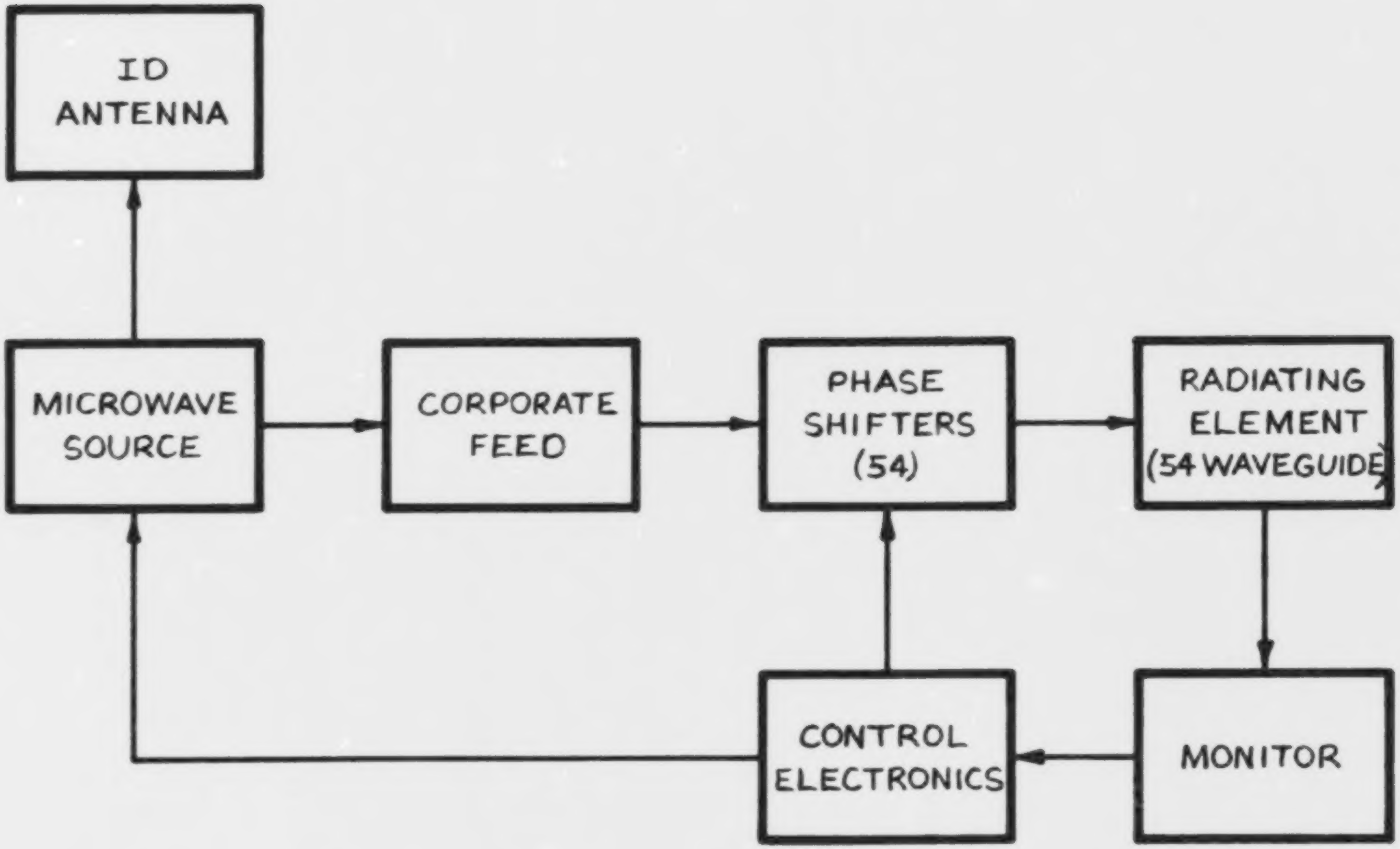

ID ANTENNA
MICROWAVE SOURCE
CORPORATE FEED
PHASE SHIFTERS (54)
RADIATING ELEMENT (54 WAVEGUIDE)
MONITOR
CONTROL ELECTRONICS

Figure 4 System Block Diagram

d. Radiating Elements

The radiating elements consist of 54 vertically mounted, slotted antennas. Each element provides a shaped radiation pattern in the elevation plane and a broad pattern in the azimuth plane.

e. Monitor

The monitor, which is a horizontally mounted waveguide, receives an output from each of the 54 radiating elements. The 54 outputs are added together to give a composite signal which is analyzed for faults.

f. I.D. Antenna

The I.D. antenna transmits the DPSK modulated data. This provides specific site information required by the MLS receiver on board the aircraft.

g. Control Electronics

The control electronics consists of the electronic circuitry which generates all the timing and data signals and controls the phase shifters throughout a scan.

h. Enclosure

The enclosure is required to protect the antenna and electronics from the environment. This includes isolating the antenna from wind loading which could cause unacceptable pertubations in the transmitted signal. The antenna radome is considered an integral part of the enclosure.

RF energy from the microwave source is fed into the corporate feed which splits the RF energy into 54 ports each with a specific phase and amplitude. The energy passes through the phase shifters where the phase can be varied in 22½° increments and is launched into the slotted waveguide radiating elements.

The monitor waveguide is coupled to each of the slotted waveguides and samples a small amount of energy from each. The signal generated is used to verify proper operation of the antenna.

An enclosure surrounds the azimuth antenna protecting it and the control electronics from adverse environmental conditions.

2.3 Specifications

MLS Azimuth Antenna Specifications

The following list describes the design specifications for the MLS azimuth antenna subsystem:

Frequency Range (Bandwidth)	5030-5090 MHz
Maximum scan Angle	$\pm 42^{\circ}$ azimuth
Beamwidth at 5060 MHz	
Scan Plane	2.0°
Orthogonal Plane	shaped[1] 0° to 20°
Sidelobe	
Scan Plane	-30 dB
Orthogonal Plane	-13 dB below horizon
Array Gain	28 dB
Power Handling	10 watts CW
Beam Scan Rate	$20{,}000^{\circ}$/sec
Maximum Average Beam Step Size	0.02°
Beam Steering Accuracy	0.02°
Polarization	vertical

[1] The pattern slope at zero (0) degrees equals 8 dB/degree or greater below the horizon. Figure's 5 and 6 describe the vertical coverage and elevation pattern for the MLS azimuth antenna subsystem.

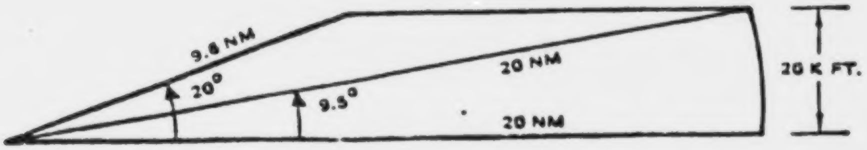

9.6 NM
20°
9.5°
20 NM
20 NM
20 K FT.

Figure 5 Vertical Coverage For Azimuth Array

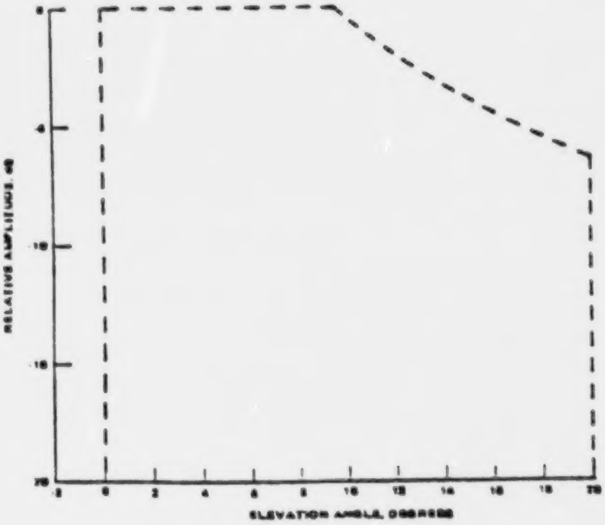


Figure 6 Elevation Pattern For Azimuth Antenna

Corporate Feed Specifications

The following list describes the design specifications for the corporate feed.

Outputs	54
Frequency Range (Bandwidth)	5030-5090 MHz
Input VSWR	1.2 maximum
Output VSWR	1.2 maximum
Isolation Between Outputs	20 dB minimum
Insertion Loss	3 dB maximum
Power Delta	± 0.5 dB maximum
Output Phase Variation	± 2.5° maximum
Temperature Range	± 65° C

Phase Shifter Specifications

The following list describes the design specifications for phase shifters.

Number of Bits	4(22.5°, 45°, 90°, 180°)
Frequency Range (Bandwidth)	5030-5090 MHz
Input VSWR	1.15 maximum
Output VSWR	1.15 maximum
Phase Variation	± 0.5° over temperature range.
Insertion Loss	2.5 dB maximum
Delta Insertion Loss Any State	0.4 dB maximum
Delta Insertion Loss per bit	0.2 dB maximum
Delta Insertion Loss Between Phase Shifters	0.5 dB maximum
Switching Time	100 ns maximum
Operating Temperature Range	± 65° C
Phase Error	4° RMS

Slotted Waveguide Radiator Specifications

Each slotted waveguide radiator must meet the following requirements:

VSWR	1.05 maximum
Phase Adjustment	8° minimum
Phase Variation	1.0° maximum
Output Variation	± 1 dB maximum
Material	WR 187 waveguide

Microwave Source Specifications

The microwave source contains an amplifier and exciter. The following are the required general specifications:

Power Output	10 watts CW
Frequency Range (Bandwidth)	5030-5090 MHz
Ambient temperature Range	
Operating	-55 to +55° C
Non Operating	-65 to +55° C

2.4 Predicted Performance

A prediction of a systems performance in this case depends on the individual part specifications. To attain an absolute through phase and amplitude error of the corporate feed, phase shifters, and slotted waveguides, an analysis of accumulated errors is needed.

Using a Taylor distribution with -30 dB sidelobes and $\bar{n}$ = 4, a worst case pattern computation results. Table 1 combines the absolute maximum losses and phase discrepencies for each part. The following derived equation is the Taylor distribution representation for this calculation.

$$P(\theta)=(1-\sigma^2_{\delta\theta})\left[2\sum_{n=1}^{M} a_n \cos\theta \cos\left[(n-\tfrac{1}{2})kd \cos\theta\right]\right]^2+\sigma^2_{\delta\theta}\cdot$$

$$2\sum_{n=1}^{M} a_n^2 + N\sigma_a^2$$

Where $\sigma^2_{\delta\theta}$ and σ^2_{ω} are assumed to be uniformly distributed.

Where : $P(\theta)$ = Power pattern (azimuth angle)

$\sigma_{\delta\theta}$ = element phase error component

a_n = excitation coefficients of the array elements

θ = polar coordinate in elevation plane.

σ_a = element amplitude error component

m = number of elements each side of origin

$k = \sqrt{w^2 \mu \epsilon}$

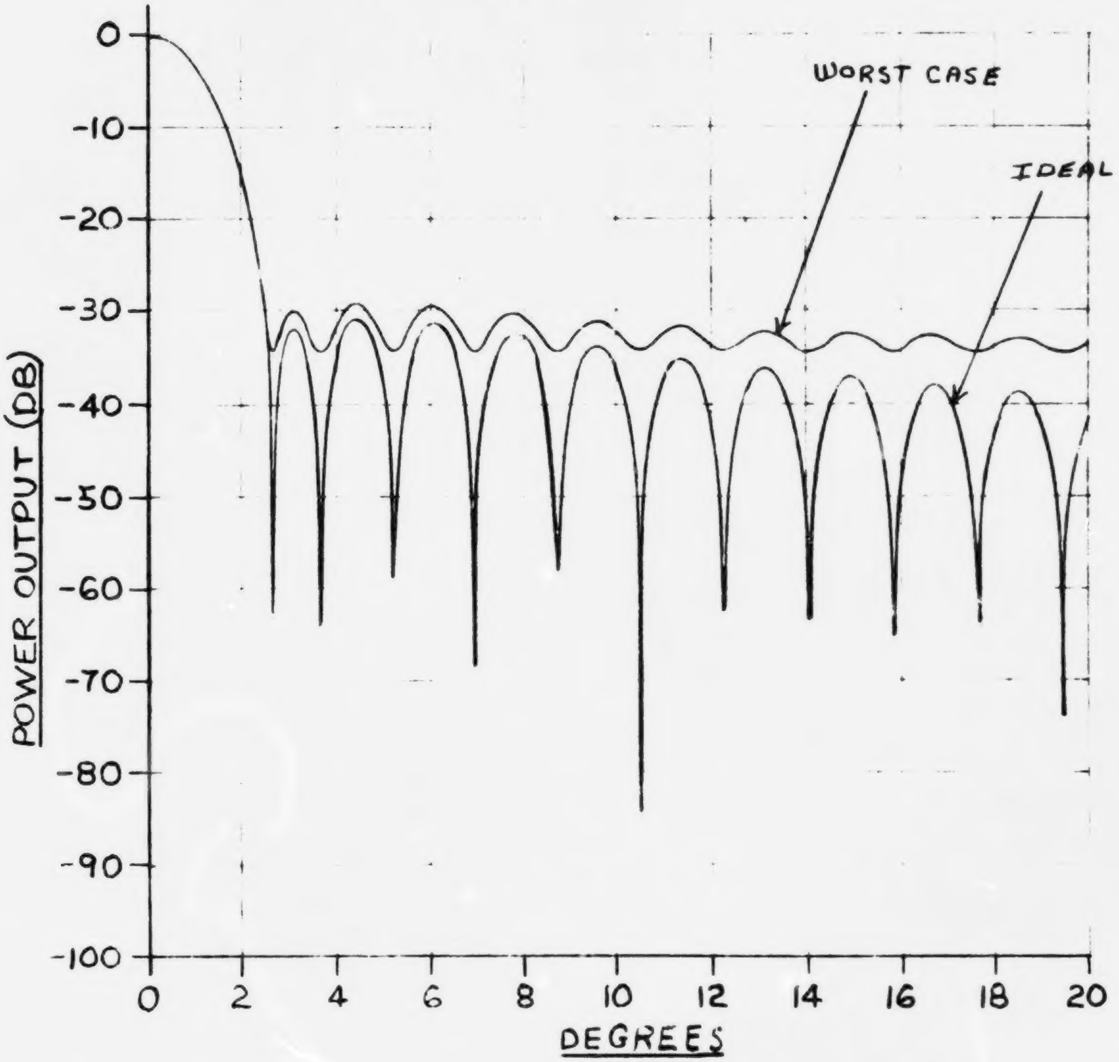
d = element separation

N = number of elements in the array

The predicted performance of the MLS azimuth antenna based on phase and amplitude accuracy determined from the preceeding specifications will result in a worst case calculated antenna pattern as shown in Figure 7.

Table 1 Phase and Amplitude Accuracy

	Amplitude	Phase
Corporate Feed	0.5 dB	5.0°
Phase Shifter	0.5 dB	3.0°
Slotted Waveguide and Coaxial line	0.1 dB	1.0°
RMS TOTAL	0.7 dB	5.9°



MLS AZIMUTH ANTENNA
BROADSIDE AZIMUTH BEAM WITH
RMS DEG = .110 (5.9 DEG.)
RMS AMP = .0070 (0.7 dB)

Figure 7 Worst Case Azimuth Radiation Pattern

2.5 Design Philosophy

The design philosophy in developing a MLS azimuth antenna was as follows:

a. The antenna must withstand adverse weather conditions without degradation of performance.

b. The system must be highly reliable.

c. The system must be cost effective.

d. The system must be easily maintainable by the appropriate personnel.

Environmental protection for the antenna subsystem depends on the sensitivity of the phase shifters, corporate feed, and waveguide elements to ambient temperatures from -65 to +65° C and high humidity. Since the phase shifters use pin diode devices, there will be no drift inside the specified temperature range for this device. The feed network will not exhibit any drift with varying temperature for element spacing since an equal path length corporate feed is used.

Each of the array elements are supported at specific spacings on a aluminium rail. Therefore a change in separation due to temperature will result in a beam angle deviation. A change of 0° would occur on the broadside beam and increase to a maximum of 0.022° angular per 20° C at the greatest scan angle of 40°. As a result the scan angle would decrease with temperature increase. Since the angle is small, approximately 0.1°, it can be accepted. The heat dissipation caused by microwave losses throughout each array is sufficiently low that cooling is not necessary.

The enclosure, which includes the radome is designed, using military standards. It protects the antenna and electronics from the weather and permits the system to operate in severe climates. The enclosure also decouples the antenna from wind-loading effects so that transmitted signals will remain within tolerance even under heavy wind conditions.

The design has been implemented to minimize maintenance and maximize interchangeability. Using field replacable components, special training needs and maintenance complexity are reduced. The antenna items which are interchangeable are the phase shifters and radiating element assemblies. Each phase shifter and waveguide assembly is factory tuned to have the same insertion phase and a correct match. No tuning or adjustments are required if any antenna module is replaced.

The monitor is designed to perform not only on-line monitoring but maintenance monitoring as well. The phase and amplitude of each element is tested by exercising their respective phase shifter. This will determine if any malfunction exists in the specific element, RF path, driver, and/or phase shifter. For on-line monitoring, the beam angle at which the monitor receives a maximum signal is compared with that of a fault free antenna to determine if an out of tolerance condition exists.

The commonality of the critical hardware not only enhances maintenance but also facilitates production and factory test. By producing more of the same to accomplish many functions, cost effectiveness is increased.

With the incorporation of military standard components and design criteria, high reliability is attained assuring long operating life.

3. DESIGN AND ANALYSIS

3.1 General

This section describes the design and analysis for each of the following parts of the MLS azimuth antenna subsystem:

a. Microwave Source
b. Corporate Feed
c. Phase Shifters
d. Slotted Waveguide Assembly
e. Mechanical Design and Assembly
f. Control Electronics

Each of these topics are discussed in detail, reviewing various designs considered, constraints, reasons for choosing certain methods, and analyses. The arrangement of the above simulates signal flow and is shown in block diagram form in Figure 4.

3.2 Microwave Source

The microwave source energizes the radiating elements by providing 10 watts CW to the phase shifters via the power divider (corporate feed) during a scan. It consists mainly of a Microwave GaS FET Power Amplifier and a Microwave Excitor.

The power amplifier is a Fujitsu Microelectronics part number CGB505110-XX. The excitor is a Frequency West part number MS-500XCL-XX. Specifications for each of these components are listed in Tables 2 and 3.

The microwave source configuration is shown in Figure 8. The excitor generates a specific frequency which is controlled by its internal crystal. The required stability must be limited to ± 10 KHz maximum. Testing over a 2 hour period demonstrated it to be 150 Hz while maintained at room temperature. To protect the output of the excitor an isolator is used. It prohibits any malfunction, short, or open circuit from damaging the excitor.

A phase shifter is used to modulate DPSK data for the I.D. antenna. It is only used during the period of time that the I.D. antenna is operating. A switch then follows which is shut off during non-transmission preventing microwave leakage to the amplifier.

The amplifier accepts a maximum input at 18 dBm but minimum at 12 dBm for saturation. It provides amplification to a 40 dBm level. This amplifier has an internal isolator which eliminates the need for an external one as used for the excitor. A four-way switch is fed by the amplifier providing power to any one of the outputs. Only two outputs are used at this time, one for the azimuth phased array antenna and the other for the I.D. antenna. The remaining two, which are now loaded are available for out-of-coverage indicator antennas.

The control signals for the microwave switches and the data to the DPSK modulator are provided by the control electronics.

Table 2 Power Amplifier Specification

Frequency Range	5031 MHz to 5091 MHz
Power Output (at +14 dBm Input)	+40. dBm Min.
Power Output Instability	1 dB Max
Input VSWR	1.5 : 1 Max.
Output VSWR	1.35 : 1 Max.
Noise Figure	12 dBc Min.
Spurious	-60 dBc Min.
Harmonics	-30 dBc Min.
DC Input Power/Current	+15 V/6.5 A Max. -15 V/0.3 A Max.
Monitoring Signals	-30 dBc ±2 dB -2 dB
ON/OFF Control	
a. Switching Time	5 uSec Max.
b. Isolation	30 dB Min.
Maximum Input Power	+18 dBm
Case Outline	Approx. 290x200x75 mm
RF Input/Output Connectors	SMA Female
DC Input Connector	25 pin D-type
Case Temperature (Operating)	-50 to +70 degrees C
Case Temperature (Non Operating)	-50 to +75 degrees C
Humidity (Relative humidity with no condensation)	up to 95%
Altitude	up to 4500 meters

Table 3 Microwave Excitor Specification

Output Frequencies	5031.0 MHz 5061.0 MHz 5090.7 MHz
Frequency Stability	± 0.0002 (± 10KHz)
Noise	-75 dB at 10 KHz in 3.1 KHz bandwidth
Harmonics	-50 dBc or better.
Output Power	22 dBm minimum.
Output Connector	SMA female.
Operating Temperature Range	-30 to +60° C

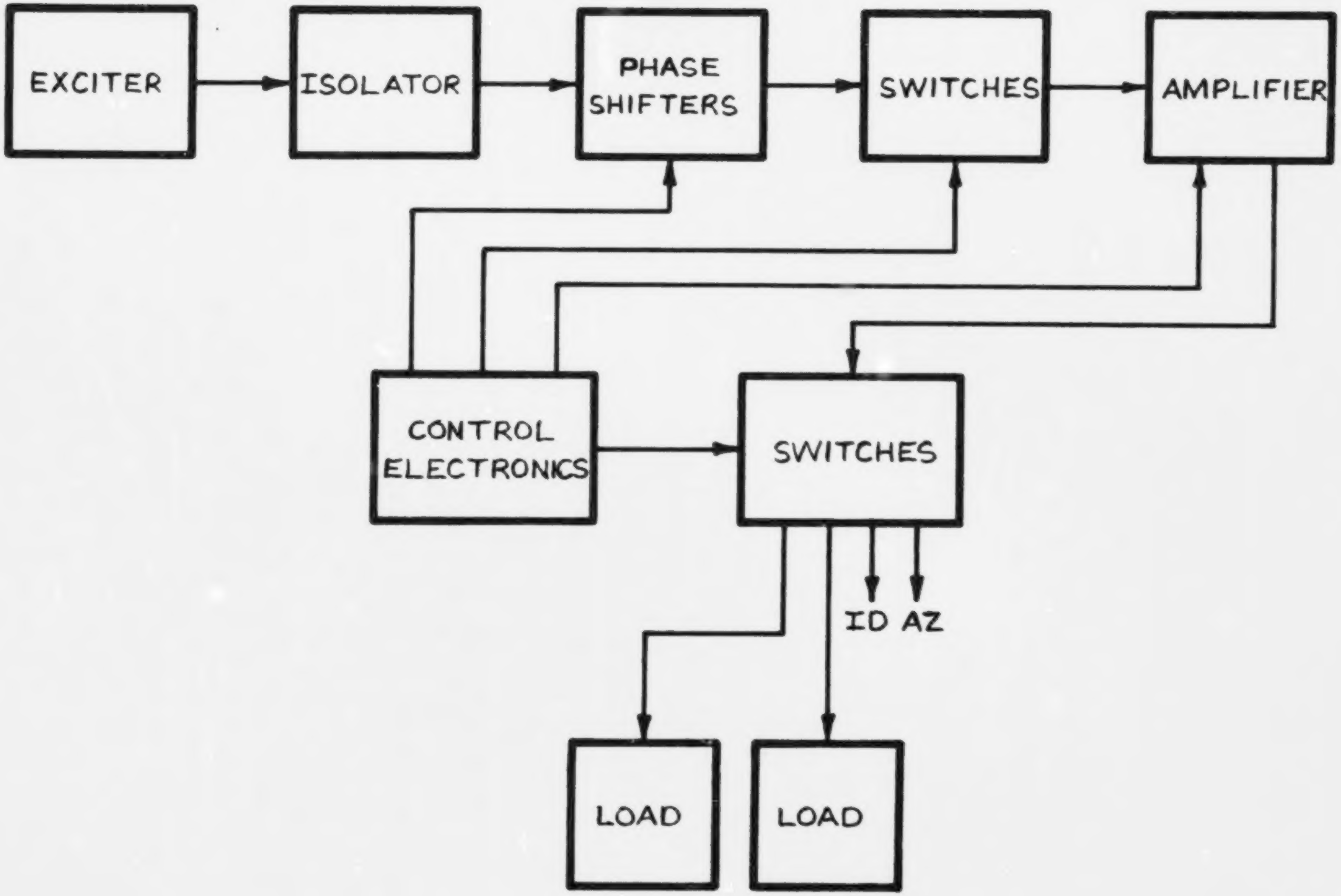

EXCITER
ISOLATOR
PHASE SHIFTERS
SWITCHES
AMPLIFIER
CONTROL ELECTRONICS
SWITCHES
ID
AZ
LOAD
LOAD

Figure 8 Microwave Source Configuration

The input signal entering the microwave amplifier is 12.4 dBm minimum not including possible connector and cable losses of 0.5 dB maximum. Following the amplifier there are additional losses due to the four-way switch and more cabling. The actual signal level at the output of the Microwave source will be approximately 39 dBm.

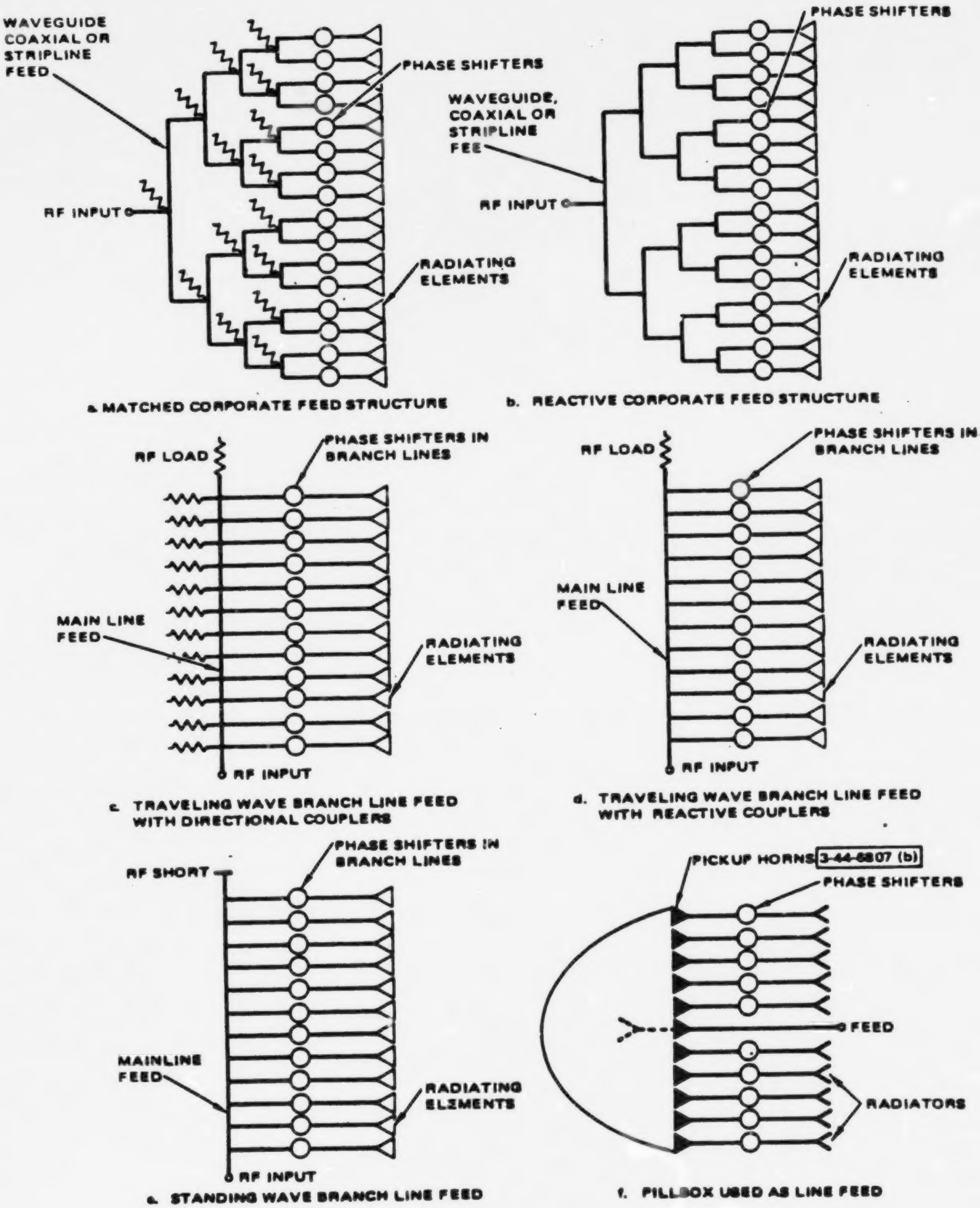
3.3 Power Distribution Network

The corporate feed divides the input RF signal into 54 outputs of identical phase with the amplitude distribution needed to meet beamwidth and scan angle requirements. Special attention has been given to the effect of temperature variation on the corporate feed due to its large physical size. The following sections outline the design process and procedures used during the development stage. Both initial specifications and final results are tabulated.

General Design

Design of the power distribution network must initially determine the type of feed and nature of transmission path which will provide the most suitable device. The basic types of feeds are parallel and series feeds as shown in Figure 9. For the parallel divider or corporate feed, a matched or a reactive feed structure can be used. In the series combination, different travelling wave configurations using directional or reactive couplers, standing wave, and optical feeds are available.

The pillbox feed, which is an optical device, is relatively inefficient and has awkward packaging requirements resulting in large arrays and is therefore rejected from further consideration. The remainder of the feeds are transmission line units and are better suited for the MLS antenna system.


WAVEGUIDE COAXIAL OR STRIPLINE FEED
PHASE SHIFTERS
RF INPUT
RADIATING ELEMENTS
PHASE SHIFTERS
WAVEGUIDE, COAXIAL OR STRIPLINE FEE
RF INPUT
RADIATING ELEMENTS
RF LOAD
PHASE SHIFTERS IN BRANCH LINES
MAIN LINE FEED
RADIATING ELEMENTS
RF INPUT
RF LOAD
PHASE SHIFTERS IN BRANCH LINES
MAIN LINE FEED
RADIATING ELEMENTS
RF INPUT
RF SHORT
PHASE SHIFTERS IN BRANCH LINES
MAINLINE FEED
RADIATING ELEMENTS
RF INPUT
PICKUP HORNS
3-44-6807 (b)
PHASE SHIFTERS
FEED
RADIATORS

a. MATCHED CORPORATE FEED STRUCTURE

b. REACTIVE CORPORATE FEED STRUCTURE

c. TRAVELING WAVE BRANCH LINE FEED WITH DIRECTIONAL COUPLERS

d. TRAVELING WAVE BRANCH LINE FEED WITH REACTIVE COUPLERS

e. STANDING WAVE BRANCH LINE FEED

f. PILLBOX USED AS LINE FEED

Figure 9 Basic Feed Networks

The two classes of feeds encompassing transmission line devices are parallel and series dividers (Figure 9 a - e). In a parallel feed, energy branches out into paths formed by a tree-like structure of power dividers (Figure 9 a,b). For a series feed, each port receives a portion of the energy that has not been coupled to a previous one (Figure 9 c - e). The parallel divider has equal RF path lengths between the input and output ports, while the series has many varying wavelength paths.

The parallel feed may be matched as in Figure 9a where four-port dividers are used, or it may be reactive as in Figure 9b where three-port dividers are used. In the first instance, the various output ports are isolated from one another and a good impedance match is always seen on each port. In the second case, the various outputs are not isolated from one another and a large mismatch may exist on each port. For an electronically steered array as is the MLS, the mismatches and poor isolation seriously degrade the antenna radiation pattern performance for all but a very few selected beam positions, and therefore restrict the use of reactive feeds.

The series feed structure may be a travelling wave with directional or reactive couplers (Figure 9 c,d) or a standing wave type (Figure 9e). The travelling wave devices are terminated in a matched load while the standing wave terminates in an RF short circuit. To couple power from the line, the travelling wave feed can use four-port directional couplers or three-port reactive couplers. The difference in these devices are similar to those in the four and three-port parallel or corporate feeds.

The choice between three-port and four-port directional couplers is dependant on the sidelobe level requirements. As the beam scans off boresight the aperture mismatch will increase. Therefore the interaction of the reflected energy with the array elements, the phase shifters, and the feed will result in a substantial increase in sidelobe levels. This will exist unless the device either absorbs the reflected energy or returns it to the radiating elements by phasing it in such a way that it is radiated as dispersed sidelobe structure. If the reflected energy is absorbed, a matched or nonreactive feed is required, otherwise the reactive feed must be designed to provide unequal and nonlinear path lengths to the array elements. The disadvantage of such a reactive feed is design complexity, the beam steering controller would have to correct the path lengths, increased beam pointing errors would result, and the decreased reflection sidelobe levels would be limited. Because of these shortcommings and those outlined earlier, a four-port matched corporate feed design was selected.

Transmission Lines

To realize a physical design of the matched corporate feed a specific type of transmission line which will best meet the system parameters must be chosen. The obvious types of transmission line candidates that may be used for the power division network include microstrip, coaxial, and waveguide.

Because of the mechanical complexity, the limited design flexibility, and high fabrication costs, the coaxial line is not favoured. It is limited to applications that require the ability of handling higher power than microstrip and avoiding the bulkiness of waveguides. For the MLS application, only low power handling is required thereby eliminating the coaxial line.

Waveguide feeds are typically bulky, mechanically complex, and costly, but have the advantage of low power loss. When microstrip is used, the feed is physically smaller, mechanically simpler, and less expensive. Its only major disadvantage is a higher loss characteristic compared to waveguides.

Taking into consideration this information, the choice of a transmission line for the matched corporate feed is microstrip. The feed designed under these conditions exhibits good thermal and mechanical stability, accurate aperture excitation control, and temperature insensitivity.

Power Splitter Design

In the design of the microwave corporate feed, power splitters with equal phase outputs and unequal power division ratios are required. The most logical designs which can be used incorporate hybrid-ring directional couplers,broadband quadrature couplers plus 90° phase shifters,or split-tee power dividers.

The principal considerations in using a hybrid-ring are the ratio of output power changes of about 1.5 dB over a 1.5 to 1 band, and the phase variation of about $\pm 4^{\circ}$ over a 1.15 to 1 band. Another method of obtaining the desired power split with equal phase outputs is by using a broadband quadrature coupler and 90° phase shifter. The coupling capability would be determined by the characteristic impedences of the various sections. This relatively complex method requires close manufacturing tolerances and hence was not used.

The split-tee divider, when constructed in microstrip, is a simple compact broadband device. It provides two isolated, equal phase, unequal amplitude outputs with a good match at each port. A stripline version of the split-tee is shown in Figure 10. The isolation resistor is a thin film resistor on a ceramic base which dissipates the reflected power that returns from the outputs. The detailed conductor configuration with the design equations are shown in Figure 11. These equations were derived on the assumption that the cross-sectional dimensions of the microstrip are very small compared to the wavelength. This will cause discontinuities resulting from corners and junctions to be negligible.

The desired split-tee power divider optimizes the phase equality transfer characteristic. However, the input VSWR is rather high at the band edges. The input VSWR can be improved by using a two-step transformer at the input as shown in Figure 12. This will be referred to as the modified

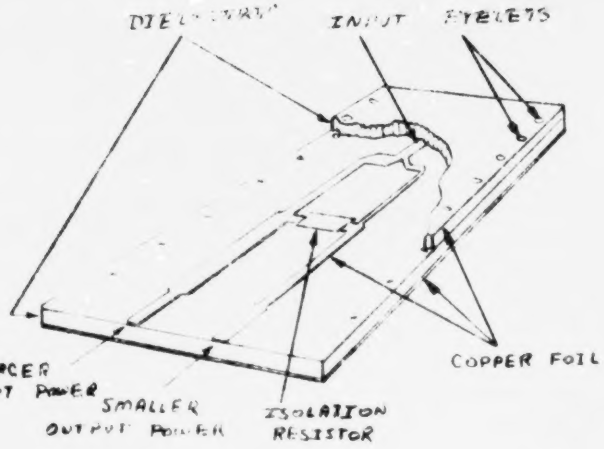
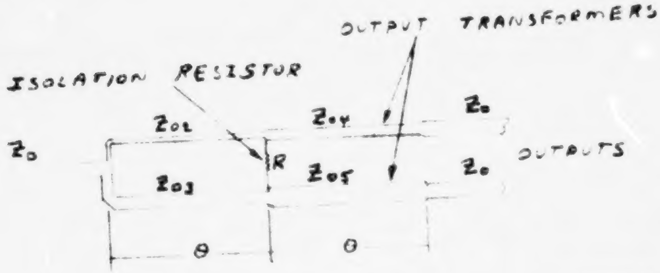

DIELECTRIC
INPUT
EYELETS
LARGER OUTPUT POWER
SMALLER OUTPUT POWER
ISOLATION RESISTOR
COPPER FOIL

Figure 10 Strip-Line Split-Tee Power Divider


OUTPUT TRANSFORMERS
ISOLATION RESISTOR
Z_0
Z_{02}
Z_{03}
R
Z_{04}
Z_{05}
Z_0
Z_0
OUTPUTS
θ
θ

$$\frac{\text{POWER AT PORT 4}}{\text{POWER AT PORT 5}} = \frac{1}{K^2}$$

CENTER FREQUENCY
AT $\theta = 90^\circ$

$$R = Z_0 \frac{1+K^2}{K}$$

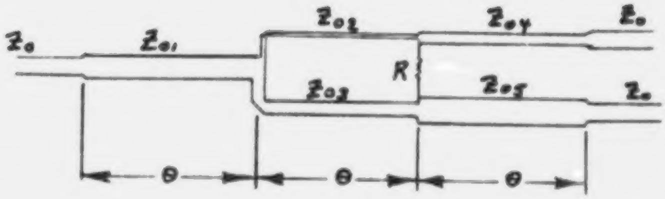
$$Z_{02} = Z_0 \sqrt{K(1+K^2)}$$

$$Z_{03} = Z_0 \sqrt{\frac{1+K^2}{K^3}}$$

$$Z_{04} = \sqrt{K}$$

$$Z_{05} = \frac{Z_0}{\sqrt{K}}$$

Figure 11 Design Equations for Split-Tee
Power Divider


Z_o
Z_{01}
Z_{02}
Z_{04}
Z_o
R
Z_{03}
Z_{05}
Z_o
θ
θ
θ

$$\frac{\text{POWER AT PORT 5}}{\text{POWER AT PORT 4}} = K^2$$

CENTER FREQUENCY
AT $\theta = 90°$

$$R = Z_o \frac{1+K^2}{K}$$

$$Z_{01} = \left(\frac{K}{1+K^2}\right)^{1/4} Z_o$$

$$Z_{02} = K^{3/4}(1+K^2)^{1/4}(Z_o)$$

$$Z_{03} = \frac{(1+K^2)^{1/4}}{K^{3/4}}(Z_o)$$

$$Z_{04} = Z_o\sqrt{K}$$

$$Z_{05} = \frac{Z_o}{\sqrt{K}}$$

Figure 12 Modified Split-Tee Power Divider

split-tee power divider. The input VSWR is improved over a wider band as well as the isolation but at the expense of output VSWR. The tradeoff proved to be desirable.

As described in the predicted performance section, the desired radiation pattern requires a Taylor 30 dB, N = 4 amplitude distribution with values as listed in Table 4. The 54 elements and corporate feed output ports are sequentially numbered 1 to 54 across the face of the array. The distribution is symetrical with elements 27 and 28 receiving equal maximum RF signal at the center of the array. The data shows a amplitude distribution of 0 dB on these center elements which decreases to -12.28 dB on the end elements (1 and 54). This is graphically represented in Figure 13.

Power division ratios necessary to accomplish the Taylor distribution are acheived by modifying the impedence of different transmission lines in the individual split-tee power dividers. The impedences Z01 to Z05 were computed using the equations in Figure 12. The K numbers (K1 - K27) identify the dividers that are placed in specific locations to determine the right half of the Taylor amplitude distribution (Figure 14). Due to symmetry the left half will be a mirror image of the right half except K1 is replaced with a through line.

Table 5 contains the impedences of the transmission lines Z01 to Z05 for the required power division ratios or K numbers. The impedences Z01 to Z05 are physically realized by varying the etch widths of the microstrip transmission lines. Figures 15 and 16 show the required circuit patterns for the split-tee power dividers.

Table 4 Corporate Feed Distribution

Element	Excitation Volts	Power dB	Normalized Power dB
27 + 28	1.555	0	7.791
26 + 29	1.548	-0.04	7.721
25 + 30	1.535	-0.12	7.584
24 + 31	1.515	-0.24	7.381
23 + 32	1.490	-0.39	7.120
22 + 33	1.458	-0.59	6.804
21 + 34	1.422	-0.83	6.443
20 + 35	1.380	-1.11	6.042
19 + 36	1.334	-1.43	5.612
18 + 37	1.284	-1.79	5.161
17 + 38	1.230	-2.20	4.695
16 + 39	1.173	-2.65	4.224
15 + 40	1.112	-3.17	3.761
14 + 41	1.048	-3.72	3.307
13 + 42	0.982	-4.34	2.872
12 + 43	0.915	-5.00	2.465
11 + 44	0.848	-5.72	2.090
10 + 45	0.781	-6.48	1.752
9 + 46	0.716	-7.29	1.455
8 + 47	0.654	-8.13	1.200
7 + 48	0.596	-8.98	0.987
6 + 49	0.544	-9.81	0.815
5 + 50	0.498	-10.59	0.680
4 + 51	0.459	-11.28	0.581
3 + 52	0.428	-11.82	0.513
2 + 53	0.406	-12.16	0.474
1 + 54	0.393	-12.28	0.461

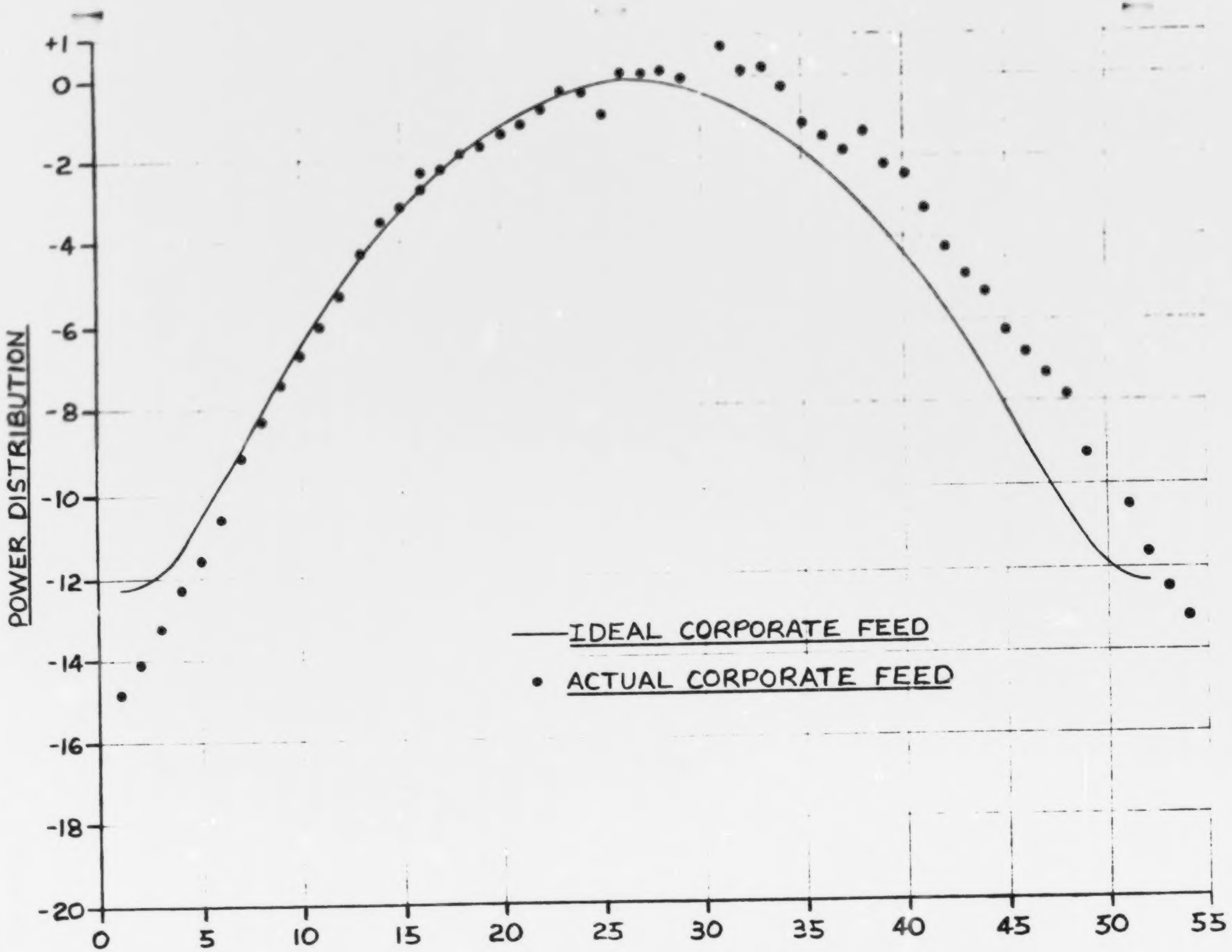


Figure 13 Taylor Distribution Plot

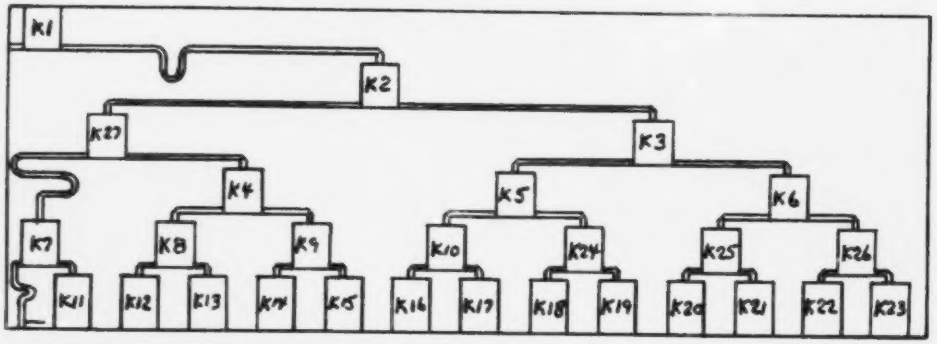

K1
K2
K27
K3
K4
K5
K6
K7
K8
K9
K10
K24
K25
K26
K11
K12
K13
K14
K15
K16
K17
K18
K19
K20
K21
K22
K23

Figure 14 Corporate Feed - Right Side

Table 5 Split-Tee Power Dividers Design Values

Divider Number	Power Division Ratio	K	Z01	Z02	Z03	Z04	Z05
K1	1.000	1	42.05	59.46	59.46	50	50
K2	2.618	1.618	40.89	98.93	37.79	63.60	39.31
K3	3.840	1.960	39.88	122.8	31.99	69.99	35.72
K4	1.290	1.136	41.96	67.67	52.46	53.29	46.92
K5	1.825	1.351	41.58	81.23	44.51	58.16	43.02
K6	1.815	1.347	41.59	80.99	44.62	58.04	43.08
K7	1.964	1.401	41.46	84.50	43.03	59.19	42.24
K8	1.095	1.046	42.03	62.24	56.84	51.15	48.88
K9	1.182	1.087	42.01	64.70	54.74	52.13	47.95
K10	1.292	1.137	41.96	67.73	52.42	53.31	46.90
K11	1.018	1.009	42.04	59.99	58.93	50.22	49.78
K12	1.037	1.018	42.04	60.55	58.39	50.46	49.55
k13	1.056	1.028	42.04	61.12	57.87	50.69	49.32
K14	1.077	1.038	42.04	61.72	57.31	50.94	49.08
K15	1.099	1.048	42.03	62.35	56.74	51.19	48.83
K16	1.123	1.060	42.03	63.04	56.13	51.47	48.57
K17	1.151	1.073	42.02	63.83	55.46	51.79	48.27
K18	1.179	1.086	42.01	64.62	54.81	52.10	47.98
K19	1.204	1.097	42.00	65.31	54.25	52.38	47.73
K20	1.216	1.103	41.99	65.65	53.99	52.51	47.61
K21	1.198	1.095	42.00	65.15	54.38	52.31	47.79
K22	1.132	1.064	42.03	63.29	55.91	51.57	48.47
K23	1.028	1.014	42.04	60.29	58.65	50.35	49.66
K24	1.420	1.192	41.88	71.13	50.09	54.58	45.80
K25	1.463	1.210	41.86	72.24	49.38	54.99	45.46
K26	1.171	1.082	42.01	64.39	54.99	52.01	48.07
K27	.469	.685	41.32	41.44	88.37	41.38	60.42

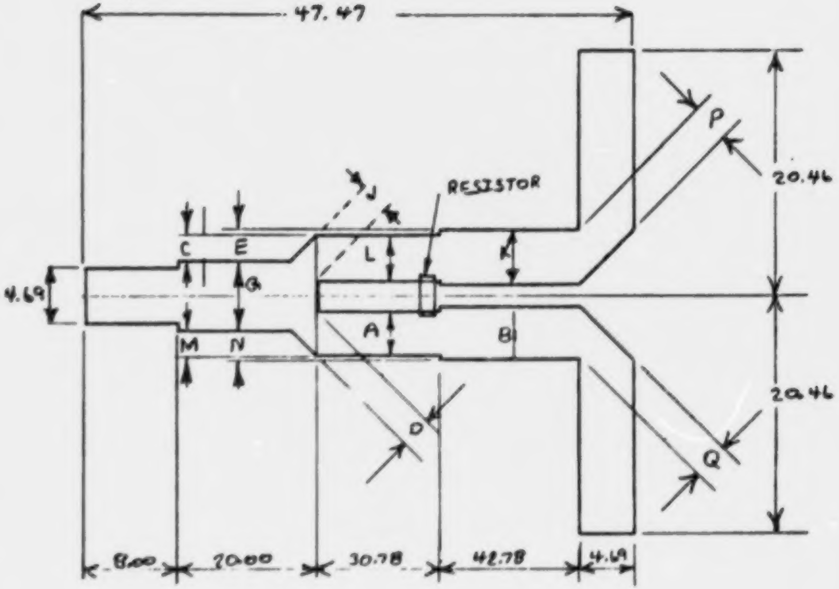

47.47
20.46
20.46
RESISTOR
P
Q
J
K
L
A
B
C
E
G
M
N
D
K
4.69
8.00
20.00
30.78
42.78
4.69

Figure 15 Power Dividers K1 - K10, K24 - K27

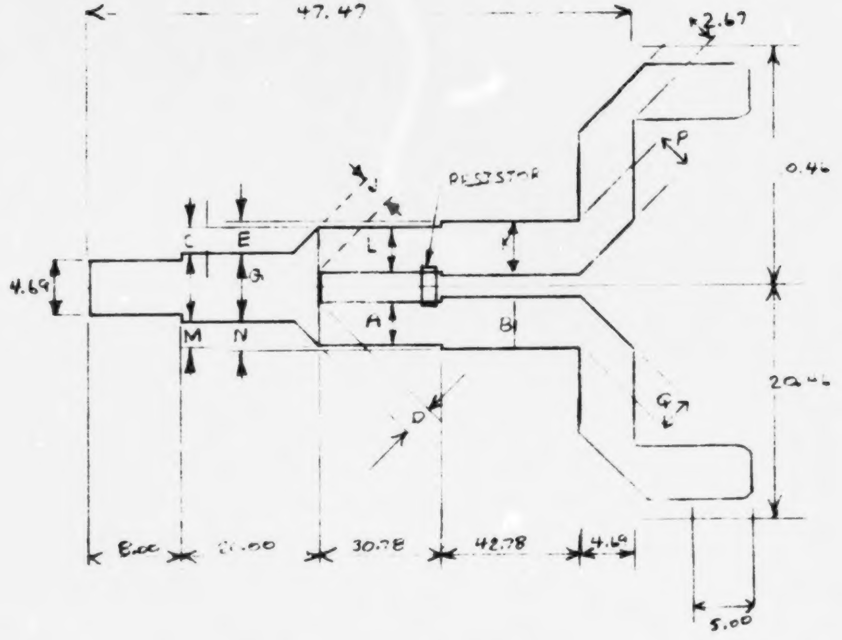

47.47
2.67
0.46
20.46
4.69
C
E
3
M
N
L
K
A
B
RESISTOR
J
P
G
D
8.00
30.78
42.78
4.69
5.00

Figure 16 Power Dividers K11 - K23

Feed Construction

The corporate feed was laid out in two halves using a glass impregnated teflon substrate known as Duroid 5880. The thickness of the Duroid is 62 mil, which is sufficient to provide a good aspect ratio for design. The two boards are purchased with an attached aluminium backplate and are connected together via an output of power divider K1.

The etching was added to the Duroid using the sputtering technique as described in the phase shifter section. The thickness of the etch was then increased by adding copper to the unmasked etch areas. For environmental protection a gold flash is deposited to all exposed copper circuitry.

The outputs of the corporate feed go to individual phase shifters through OSP connectors which have a phase insertion variation of $\pm 2.5^{\circ}$. These connectors can also be obtained with a phase variation of $\pm 1^{\circ}$. Their VSWR in the 5 GHz range is good at approximately 1.1. Construction information on the corporate feed is as follows:

a. Dimensions

The corporate feed requires its 54 outputs to be spaced .611 λ apart, so as to physically align with the correct spacing from corporate feed outputs to the slotted waveguides input connectors. Thus the size of the corporate feed will be approximately 0.4 x 2.0 meters.

b. Substrate

The substrate is Duroid 5880, manufactured by Rogers. Because of the difficulty involved with producing a 0.4x1.0 meter piece of duroid, it was felt that two pieces 0.4x2.0 meter would perform the job. Figure 17 illustrates the method used to connect the two substrate sections. The Duroid thickness was controlled to 62 ± 2 mil. No specifications were given to Rogers on the peak to peak surface variation or the uniformity in dielectric constant, because this was the first attempt by Rogers to fabricate such a large piece. It was decided that an inspection would be carried out by Canadian Astronautics Limited to determine whether the Duroid was useable. Three pieces were fabricated and all were found to maintain good characteristics over the whole area.

c. Circuit

All the necessary dimensions for the microstrip circuit are shown on the corporate feed drawing. The final corporate feed was cut to within 0.5 mm on all sides, in order for it to fit in the corporate feed housing. The isolation resistors were chip resistors with values of 90 ± 5 ohms.

The two sections of the corporate feed were mounted onto a single base plate and the four sides of the box screwed onto this plate.

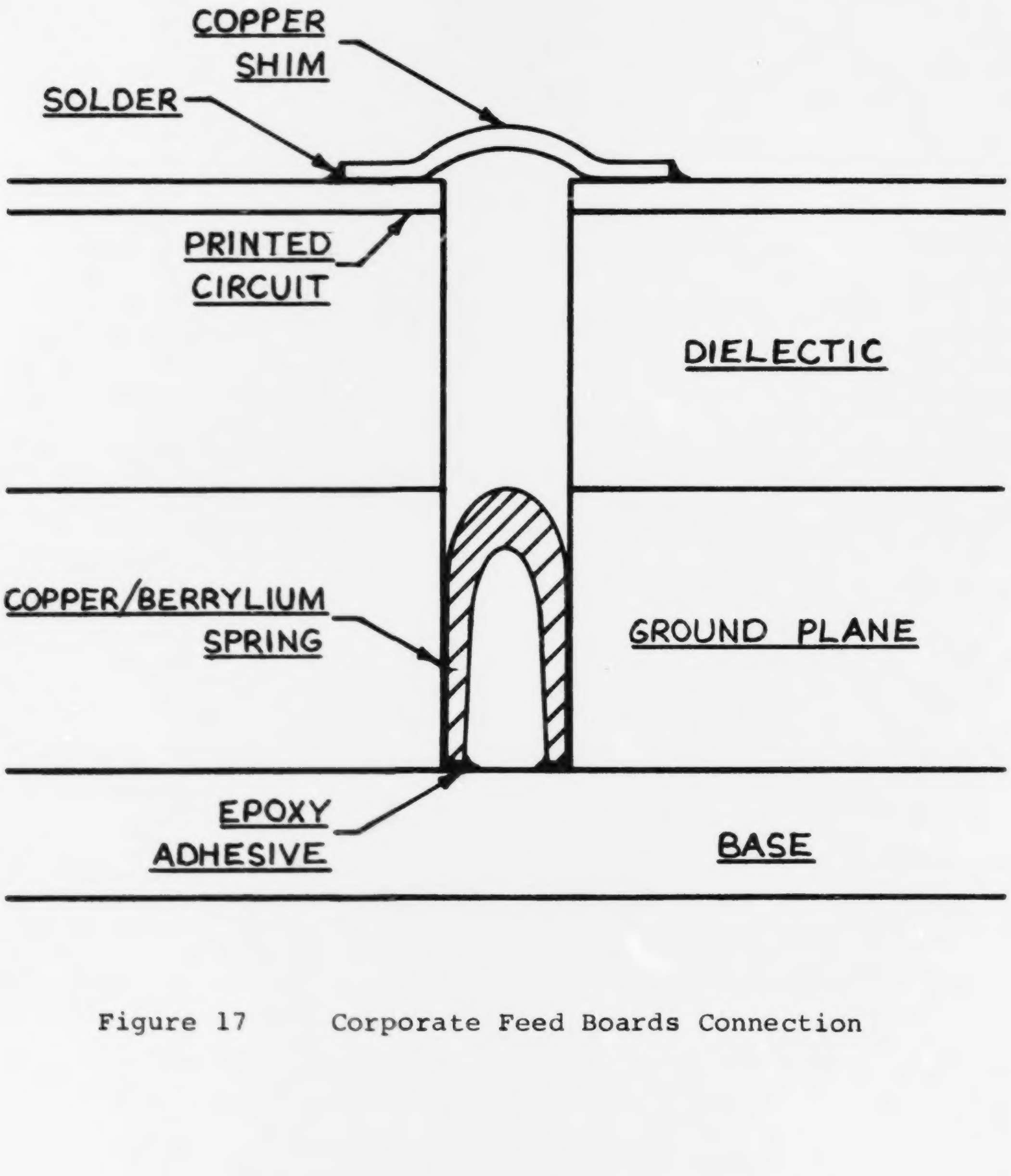

COPPER
SHIM
SOLDER
PRINTED
CIRCUIT
DIELECTIC
COPPER/BERRYLIUM
SPRING
GROUND PLANE
EPOXY
ADHESIVE
BASE

Figure 17 Corporate Feed Boards Connection

d. Tuning & Adjustments

The corporate feed was designed to have a Taylor distribution across its output ports. The specifications on the amplitude and phase are extremely tight; ± 0.5 dB, ± 2.5 deg. for amplitude and phase on each output port, respectively.

Thus a technique for fine tuning the phase as well as the amplitude was considered. To achieve the phase accuracy each output port had the identical transmission line length from the input. This involved extending some lines by use of a trombone. There are numerous discontinuities that the RF signal traversing from the input to each individual output must encounter. These discontinuities tend to alter the phase and hence must be compensated to achieve identical phase across the outputs. A phase trimming stub was inserted at the design stage for the fine tuning within 15°. For more extreme phase variations, ceramic laid on top of the microstrip line was used to delay the phase through the microstrip line. Up to approximately 60° of delay can be achieved before any appreciable effect on insertion loss and VSWR is noticed.

A technique for fine tuning of the amplitude was also invented. By observing the split-tee power dividers, one will notice that the two transmission lines directly after the split, control the major portion of the power ratio. If the Taylor distribution deviated at some outputs, then by trimming away some of the microstrip line (varying the impedance) the correct amplitude can be gained at each output. This also has a tendency to degrade the VSWR on each power splitter. But, because the power splitters are up to five levels of splitters from the input power divider, the effect on the input VSWR can be tolerated.

The testing of the corporated feed was performed on the automatic network analyzer. This was necessary to achieve the required accuracy of amplitude and phase measurement. It was found that placing the top cover of the corporate feed over the microstrip circuit caused surface waves propogation in the cavity. Microwave energy absorbing material was placed at convenient locations in the cavity to reduce the effects of the surface waves.

Experimental Results

The corporate feed distribution was measured on the automatic network analyzer with all outputs loaded except the one under measurement. The results were then printed out; S_{11} refers to the return loss looking into the input port, S_{21} refers to insertion loss between the input and the output port under measurement. The phase of S_{21} is the through phase between the input and the output port. The results are tabulated in Appendix 8. The diagram showing the actual power distribution superimposed over the ideal numbers is Figure 13.

3.4 Phase Shifter

Each slotted waveguide element of the antenna array contributes a component radiation pattern to the cumulative antenna array radiation pattern. If all phase shifters are set to zero and thus provide a constant phase delay through each phase shifter, the beam will be pointed to zero degrees in azimuth angle referenced to the centerline of the array.

Applying the appropriate phase gradient to the elements of the antenna array allows the radiated beam to be directionally positioned in the azimuth plane. The MLS antenna beam can be made to move or "scan" by selectively varying the relative phase of the signal fed to each of the slotted waveguide radiators.

Phase Shifter Requirements

Our required phase shifter is a microwave device which delays in time the output signal relative to the input signal in discrete steps from 0 to 360° of phase. Phase shifters for MLS applications are narrow band devices which must operate over a wide range of environmental conditions. Special emphasis must be placed on controlling the per device cost due to the large number of phase shifters usdd in a fully filled phased array design.

The design specification for the MLS phase shifter is attached as Table 6.

Table 6 Phase Shifter Specification

- No of Bits 4 22.5°, 45°, 90°, 180°
- RMS phase error = 4 Deg. Max RMS over freq. range
- Frequency of operation 5.030 to 5.090 GHz
- Input VSWR 1.15 Max.
- Output VSWR 1.15 Max.
- Insertion loss = 2.5 dB Max
- Delta Insertion loss any state = 0.4 dB Max
- Delta Insertion loss per bit = 0.2 dB Max
- Switching time = 100 ns Max
- Operating temperature range $\pm 65^\circ$ C
- Change of phase with Temp ± ½ Deg over $\pm 65^\circ$ C
- Delta insertion loss between phase shifters 0.5 dB

The phase shifters are digitally controlled and therefore the phase shift must take place in discrete steps. The size of the minimum phase shift increment contributes to the maximum expected sidelobe level during scanning. The phase shifters will be digitally controlled by the bits of a binary word. If controlled by three bits the minimum phase increment would be $(360^\circ / 2^3)$ or 45°. Four bit control yields 22.5 degree resolution and 5 bits provides an 11.25° increment.

Smaller phase increments require increasingly complex phase shifters, phase shifter control and phase shifter switching speed. In the trade off between minimum phase shift and sidelobe level, the Hughes Aircraft Co. study shows that four bit shifters would be the most cost effective choice while providing a dynamic radiation pattern with sidelobes sufficiently low for MLS use. The 4-bit phase shifter will consist of four switchable phase shift circuits in series as shown in Figure 18.

To simplify production and to control costs one phase shifter design will be used for all system designs.

A prime requirement for the phase shifter is ease of removal and replacement. All phase shifters must exhibit the same operating characteristics including absolute or through phase delay allowing replacement of phase shifters without recalibration or tuning. This is especially important as Mean Time to Repair, MTTR,of better than 30 minutes is required by the final user of the system.

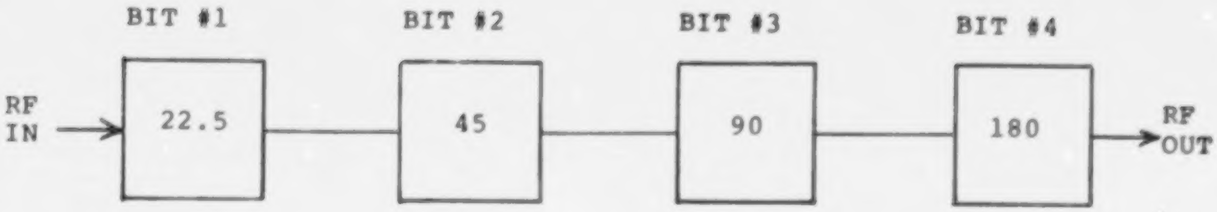


Figure 18 Phase Shifter Block Diagram

Phase Shifter Design

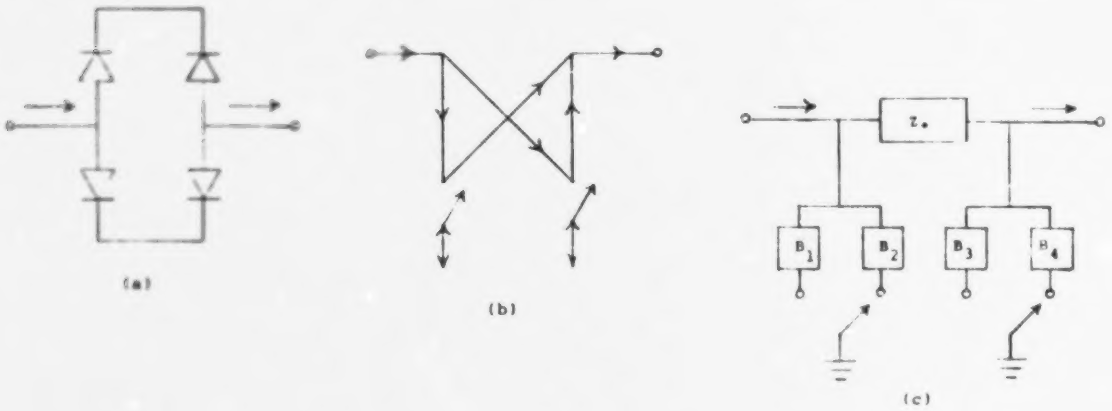
The two generally recognized methods of providing electronically controlled phase shift at these frequencies are the use of ferrites or PIN diodes. Phase shift using ferrites is accomplished by changing the permeability of a ferrite material located in the transmission path. PIN diodes behave like a capacitor which can have a plasma injected between its conducting plates by a bias current. Phase shift using PIN diodes results from the reactance switching of the diode capacitance and the resulting rerouting of the microwave currents through the circuits containing the diodes.

PIN diodes have several advantages over ferrites. PIN diodes are small in comparison to the wavelength at which they operate and are capable of faster switching speeds than ferrite devices while also using simpler driver circuits. Diode phase shifters are reciprocal devices as opposed to ferrite phase shifters which are subject to hysteresis. PIN diodes cannot handle as much power as ferrites but are more than adaquet to handle the power levels associated with MLS. Temperature variation has negligible effect on the insertion phase or phase-shift of PIN diode phase shifters providing a substantial advantage over ferrite devices. PIN diodes are also compatable with printed circuit fabrication due to their dimensions and are better suited to low cost microstrip design.

As mentioned previously the phase shifter is composed of 4 switchable sections; 22.5°, 45°, 90° and 180°, representing 4 phase bits. A section or bit may be realized by the following circuit designs:

a. Switched line phase bit
b. Hybrid-coupled phase bit
c. Loaded line phase bit

Simplified circuit diagrams of these shifter types are shown in Figure 19.



(a) (b) (c)

Figure 19 Types of Phase Shifters

Of the different types of phase shifters the operation of the switched line phase shifter is the easiest to understand. It simply switches from a line of one length or phase delay to a line of a different length and thus a different phase delay. It requires a large amount of board space, four diodes per bit and complementary drive signals for the pairs of diodes. The loaded line type phase shifter only requires two diodes per bit but is limited to phase shifts of 45° or less. The reflection type hybrid coupled phase shifter uses two diodes per bit, can be designed for any phase shift, and requires only a single control line. It is the basic design used in our phase shifter.

Hybrid Coupler Trades

The required properties of the hybrid coupler in Figure 20 are: 1) it must provide a 3 dB power split for the two output arms, and 2) there must be a 90° phase difference in its output signals. Given these properties, it is possible to show that reflections from symmetric terminations on the 3 dB arms will exit the fourth port of the hybrid. The 3 dB 90° properties of the coupler can be realized in TEM transmission line with at least three different circuit types. The branch line hybrid coupler, the rat race coupler with a 90° line section added to one of its output ports, and the backward wave proximity coupled hybrid were possible design routes.

The branch line hybrid coupler was selected due to a reasonably straightforward design procedure and the advantage

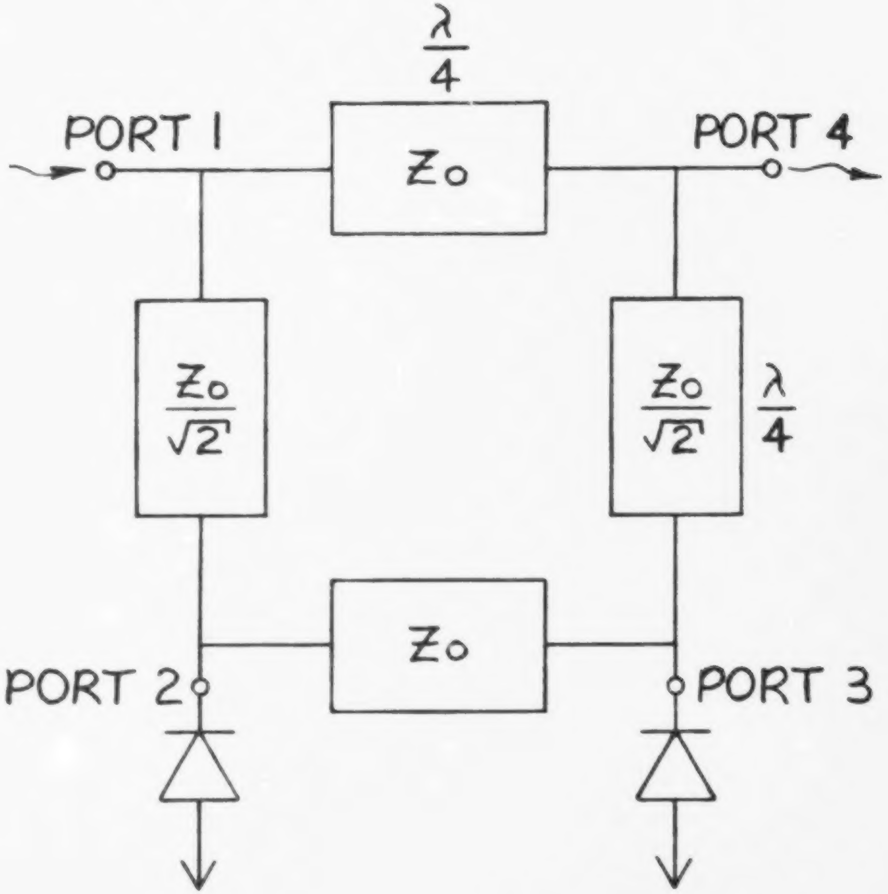

$\frac{\lambda}{4}$
PORT 1
Z_o
PORT 4
$\frac{Z_o}{\sqrt{2}}$
$\frac{Z_o}{\sqrt{2}}$
$\frac{\lambda}{4}$
Z_o
PORT 2
PORT 3

Figure 20 Branch Line Hybrid Phase Shifter Bit

that it can be formed in one plane making it suitable for microstrip fabrication as only a single conductor pattern need be etched. On the other hand, it is limited to about 5-10 percent bandwidth due to the fact that the 90° phase difference, the 3 dB power split at its output arms, the input transmission match, and the directivity are realized perfectly at only the frequency for which all line lengths are 90°. This is not a problem, for our application as only a 1 percent bandwidth is needed. A disadvantage stems however from the fact that in a 50Ω system, two of the arms of the coupler must be made with a characteristic impedance of 35Ω resulting in a fairly wide center conductor. At higher frequencies the width of this line becomes comparable to its length. When this is the case the intersection of the lines requires modelling as a complex network.

The initial design of the 4 bit reflection-type phase shifter consisted of a termination behind the pin diode that was very complex. This termination was very difficult to achieve for the specifictions given and it took many weeks of fine tuning iterations to get a working phase shifter. The concept was correct for obtaining 0.50 dB worst case insertion loss change but the technique of using the bonding wire inductance to accomplish this was an extremely difficult procedure to achieve with any repeatability. Only one phase shifter was made using this technique and the results are questionable due to the measuring equipment used.

A solution for phase shifter design was needed that would meet specifications and would be repeatable. The approach taken was to trade off insertion loss errors for improvement in phase errors.

Design of Hybrid Coupler Phase Shifter

The design of the reflection type phase shifters was made, around the 3 dB hybrid coupler. The coupler was loaded with identical reflecting diode terminations.

In microstrip at low frequencies the junctions of the hybrid can be considered as interconnected transmission lines, but at higher frequencies the junction effects can no longer be ignored. When the size of the junctions are no longer negligible compared to a wavelength, there can be appreciable equivalent reactances at the junctions.

An equivalent circuit for the two-branch coupler, with junction effects, is given in Figure 21. L represents a section of microstrip line and J represents any junction effects.

The equivalent circuit of the two-branch coupler including junction reactances is given in Figure 22 where S represents the symmetry plane. Once this equivalent circuit has been identified, then the task of optimizing the transmission line lengths to obtain the best performance of the 3 dB directional coupler can be performed.

A reflection phase bit can be designed by terminating coupled ports of a quadrature hybrid coupler into identical reflection coefficients Γ as depicted in Figure 23. The scattering matrix for such a phase shifter is obtained from

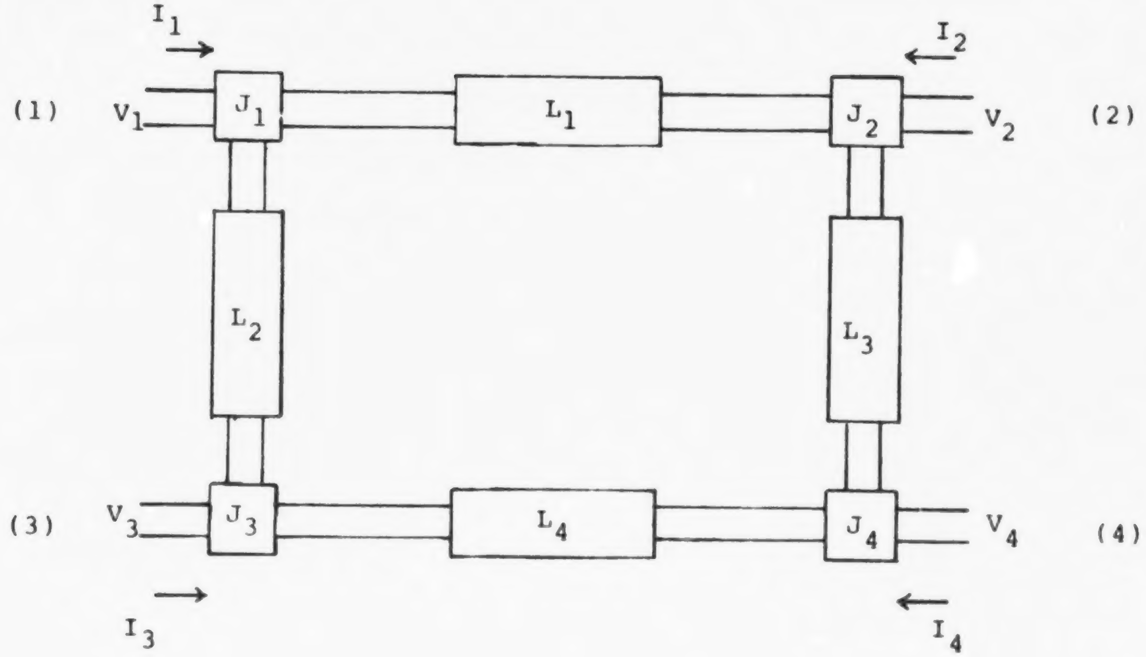

I1
I2
(1)
V1
J1
L1
J2
V2
(2)
L2
L3
(3)
V3
J3
L4
J4
V4
(4)
I3
I4

Figure 21 Equivalent Circuit For Two Branch Coupler, Showing Line and Junction Components

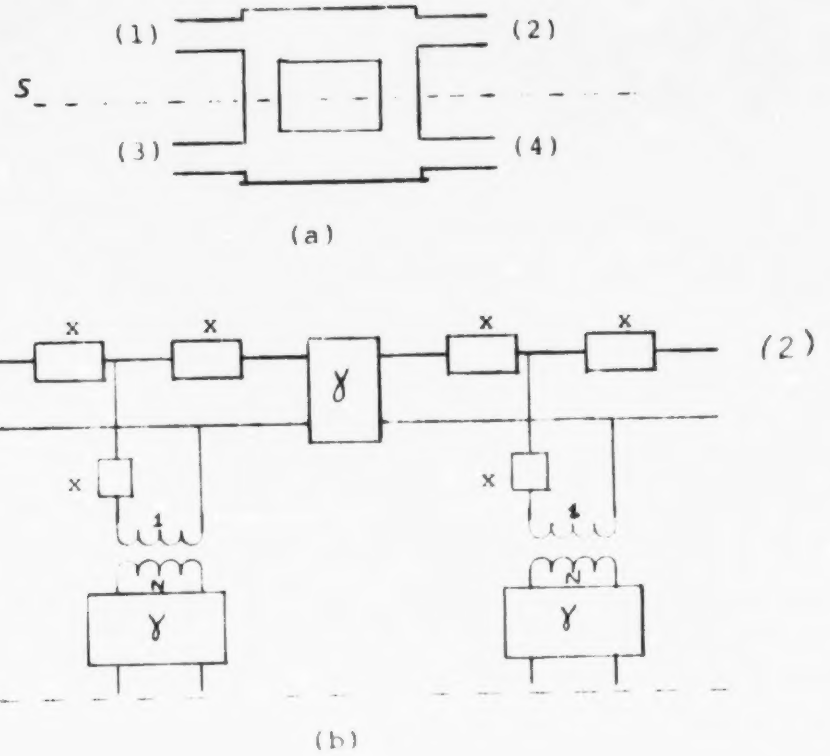

(1)
(2)
S
(3)
(4)
(a)
x
x
x
x
(1)
(2)
γ
x
x
1
1
N
N
γ
γ
S
(b)

Figure 22 Two Branch Coupler and Equivalent Circuit With Junction Components

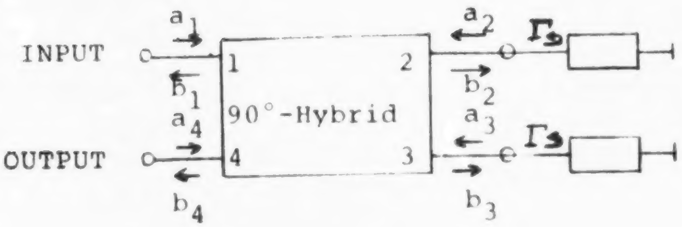

INPUT
OUTPUT
a_1
b_1
a_4
b_4
1
2
4
3
90°-Hybrid
a_2
b_2
a_3
b_3
Γ_S
Γ_S

Figure 23 Reflection Type Phase Shifter

an S-matrix of the hybrid by eliminating the wave variables b_2 and b_3 and can be written as:

$$\begin{bmatrix} b_1 \\ b_4 \end{bmatrix} = \begin{bmatrix} S_{11_p} & S_{14_p} \\ S_{41_p} & S_{44_p} \end{bmatrix} \begin{bmatrix} a_1 \\ a_4 \end{bmatrix}$$

where

$$S_{11p} = S_{44p} = S_{11} + \frac{(S^2{}_{21} + S^2{}_{31})\,(1 - S_{11}\Gamma) \;+ 2\,S_{21}\,S_{31}\,S_{41}\Gamma^2}{(1 - S_{11}\Gamma)^2 - S^2{}_{41}\Gamma^2} \tag{3.1}$$

$$S_{14p} = S_{41p} = S_{41} + \frac{(S^2{}_{21} + S^2{}_{31})\,S_{41}\Gamma^2 + 25_{21}\,S_{31}\Gamma(1 - S_{11}\Gamma)}{(1 - S_{11}\Gamma)^2 - S^2{}_{41}\Gamma^2} \tag{3.2}$$

If one assumes a reasonable match and directivity of the hybrid then $|S_{11}|$ and $|S_{41}| \ll 1$.

And using this approximation equations (3.1) and (3.2) become,

$$S_{11p} = \left|S_{11}\right| \left[e^{j\theta_1} + \Gamma^2 e^{j(\theta_2+\theta_3+\theta_4)} + 2\left|S_{11}\right|\Gamma^3 e^{j(\theta_1+\theta_2+\theta_3+\theta_4)}\right] \tag{3.3}$$

$$\begin{aligned} S_{41p} = {} & \Gamma e^{j(\theta_2+\theta_3)} + \left|S_{11}\right| e^{j\theta_4} + \Gamma^2 \left|S_{11}\right| e^{j(\theta_1+\theta_2+\theta_3)} \\ & -2\Gamma\left|S_{11}\right|^2 e^{j(\theta_2+\theta_3)} - 3\Gamma^3 \left|S_{11}\right|^2 e^{j(2\theta_1+\theta_2+\theta_3)} \\ & + \Gamma^3 \left|S_{11}\right|^2 e^{j(\theta_2+\theta_3+2\theta_4)} \end{aligned} \tag{3.4}$$

where θ_1, θ_2, ... etc. are the phases of S_{11}, S_{21}, ... respectively.

Since generally the phase values associated with S_{11}, S_{21}, S_{31} and S_{41} in an imperfect hybrid depend upon the specific cause of imperfection, exact values of phase shifter reflection and transmission coefficients are difficult to evaluate. Thus it is useful to determine the worst case values of VSWR, insertion loss.

Taking $\Gamma = e^{j\theta}$ the worst case value of S_{11p} and S_{41p} is shown to be,

$$\left|S_{11p}\right|_{wc} = 2\left|S_{11}\right| \left(1 + \left|S_{11}\right|\right) \tag{3.5}$$

$$\left|S_{41p}\right|_{wc} = \sqrt{1 - \left|S_{11p}\right|^2_{wc}} \tag{3.6}$$

Matching Network Design

The transmission match of any hybrid coupler phase shifter is dependent only on the design of the hybrid coupler and, thus, may be performed separately from the design of the matching network.

The matching network controls two parameters. Depending on the selection of matching configurations, the phase shift through the hybrid bit can be altered as well as the insertion loss. It was found that by configuring the matching network as in Figure 24, an optimization of tradeoffs can be determined. Figure 25 shows the equivalent circuit of the matching network where L_S is the bonding wire inductance, C_J is the junction capacitance, and R_R and R_F are the reverse and forward resistance, respectively. C_S is the open circuited microstrip line equivalent capacitance.

where

$$C_S = \frac{\tan \beta \ell}{Z_O w}$$

and

$$R_R = R_F \triangleq R_S$$

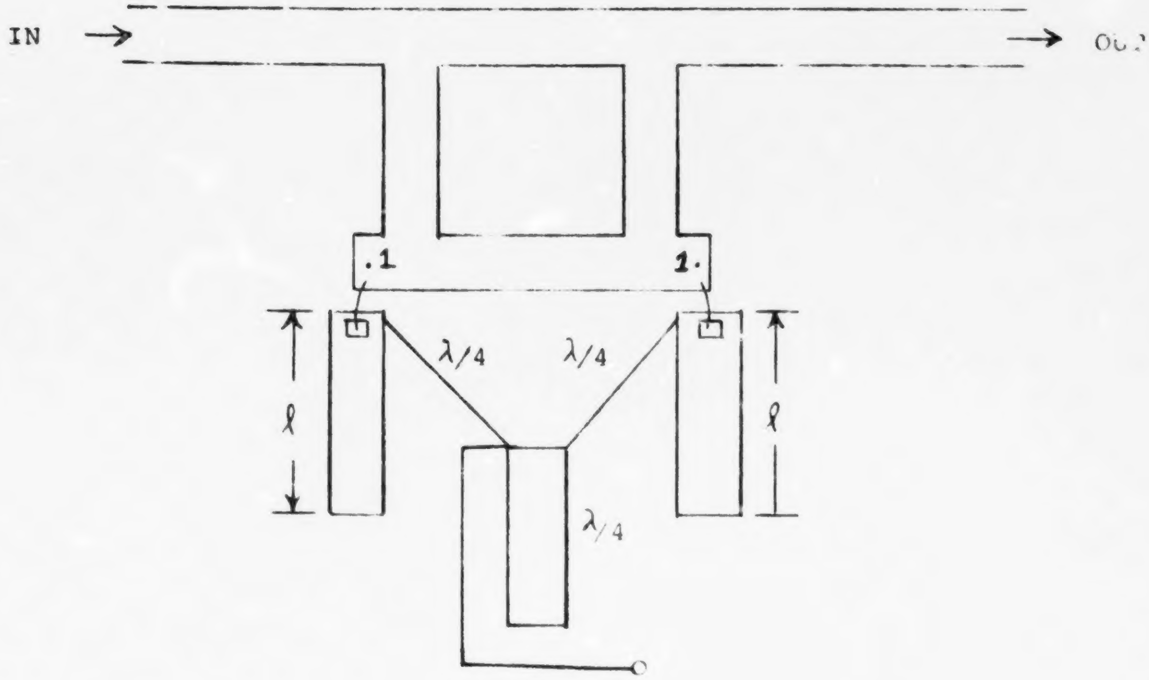

IN
OUT
.1
1.
λ/4
λ/4
ℓ
ℓ
λ/4

Figure 24 Reflection Type Phase Shifter Microstrip Design

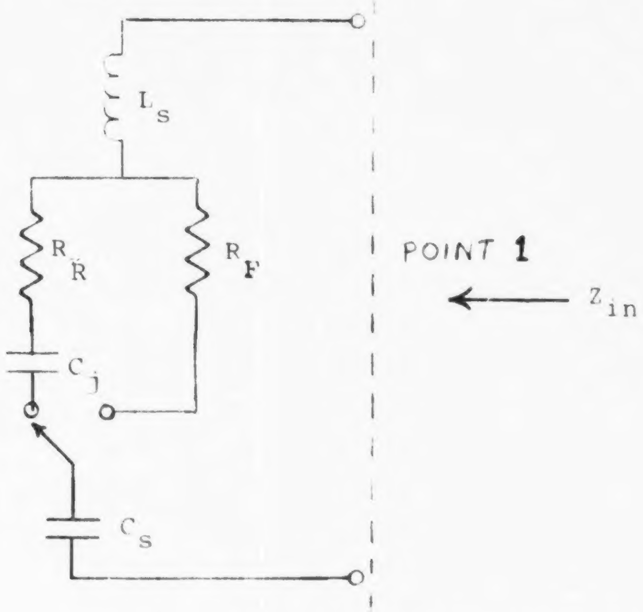

L_s
R_R
R_F
C_j
C_s
POINT 1
Z_{in}

Figure 25 Equivalent Circuit of Reflection Port

ANALYSIS OF MATCHING NETWORK

$$Z_{IN} = jwL_S + R_S + \frac{1}{jwC_J} + \frac{1}{jwC_S} \qquad (3.7)$$

where $C_J = .15$ pF for 0 ma.

and $C_J >> 10$ pF for 20 ma.

$$\Gamma = \frac{Z_{IN} - Z_0}{Z_{IN} + Z_0} = \frac{R_S - Z_0 + jwL_S - j\left[\frac{1}{wC_J} + \frac{1}{wC_S}\right]}{R_S + Z_0 + jwL_S - j\left[\frac{1}{wC_J} + \frac{1}{wC_S}\right]} \qquad (3.8)$$

$$\Gamma = \frac{\left(R_S - Z_0 + j\left[wL_S - \frac{1}{wC_J} - \frac{1}{wC_S}\right]\right)\left(R_S + Z_0 - j\left[wL_S - \frac{1}{wC_J} + \frac{1}{wC_S}\right]\right)}{(R_S + Z_0)^2 + \left(wL_S - \frac{1}{wC_J} - \frac{1}{wC_S}\right)^2} \qquad (3.9)$$

$$\Gamma = \frac{(R_S - Z_0)(R_S + Z_0) + \left[wL_S - \frac{1}{wC_J} - \frac{1}{wC_S}\right]^2 + 2j\,Z_0\left[wL_S - \frac{1}{wC_J} - \frac{1}{wC_S}\right]}{(R_S + Z_0)^2 + \left(wL_S - \frac{1}{wC_J} - \frac{1}{wC_S}\right)^2} \qquad (3.10)$$

$$\sphericalangle\Gamma = \tan^{-1}\left[\frac{2\,Z_0\left(wL_S - \frac{1}{wC_J} - \frac{1}{wC_S}\right)}{(R_S - Z_0)(R_S + Z_0) + \left(wL_S - \frac{1}{wC_J} - \frac{1}{wC_S}\right)^2}\right] \qquad (3.11)$$

$\Gamma_{OFF} \quad I = 0_{ma}, \; C_J = .15 \text{ pF}$

$\Gamma_{ON} \quad I = 20_{ma}, \; C_J >> 10 \text{ pF}$

Because of the physical constraints the minimum bonding wire length is approximately 0.75mm.

Therefore

$$L_S = .34 \text{ nH}$$

$\underline{\Gamma_{OFF}}$

$$\left| \frac{1}{wC_J} \right| = 209.7 \; \Omega$$

$$\left| wL_S \right| = 10.8 \; \Omega$$

Therefore $\left| \frac{1}{wC_J} \right| >> \left| wL_S \right|$ and $Z_O >> R_S$

$$< \Gamma_{OFF} = \tan^{-1} \left[\frac{-2 \; Z_O \left(\frac{1}{wC_J} + \frac{1}{wC_S}\right)}{-Z_O{}^2 + \left(\frac{1}{wC_J} + \frac{1}{wC_S}\right)^2} \right] \qquad (3.12)$$

$\underline{\Gamma_{ON}}$

$$\left| \frac{1}{wC_J} \right| << 3.15 \; \Omega$$

$$\left| wL_S \right| = 10.8 \; \Omega$$

Therefore

$\left| wL_S \right| >> \left| \frac{1}{wC_J} \right|$ and $Z_O >> R_S$

$$< \Gamma_{ON} = \tan^{-1} \left[\frac{2 \; Z_O \left(wL_S - \frac{1}{wC_S}\right)}{-Z_O{}^2 + \left(wL_S - \frac{1}{wC_S}\right)^2} \right] \qquad (3.13)$$

Therefore

$$\phi = \angle \Gamma_{OFF} - \angle \Gamma_{ON}$$

$$\phi = \tan^{-1}\left[\frac{-2\,Z_0\left(\frac{1}{\omega C_J} + \frac{1}{\omega C_S}\right)}{-Z_0^{\,2} + \left(\frac{1}{\omega C_J} + \frac{1}{\omega C_S}\right)^2}\right] - \tan^{-1}\left[\frac{2Z_0\left(\omega L_S - \frac{1}{\omega C_S}\right)}{-Z_0^{\,2} + \left(\omega L_S - \frac{1}{\omega C_S}\right)^2}\right] \tag{3.14}$$

ℓ	C_S (pf)	ϕ_1 (deg)	ϕ_2 (deg)	$-\Delta\phi$ (deg)
0	.00	-0.00	-0.00	0.00
λ/32	.125	-12.38	-23.50	-11.12
λ/16	.2605	-17.21	-48.90	-31.70
3λ/32	.4203	-19.93	-75.95	-56.02
λ/8	.6290	-21.79	+76.22	-81.99
5λ/32	.9414	-23.24	+48.68	-108.08
6λ/32	1.519	-24.49	+22.44	-133.07
7λ/32	3.162	-25.69	-1.95	-156.30
λ/4	∞	-26.82	-24.38	-177.56
9/32λ	-3.162	-28.11	-45.07	-196.96
10/32λ	-1.519	-29.64	-65.45	-214.81

Figure 26 is a graphical representation of reflection port phase as a function of the length of the reflecting microstrip line.

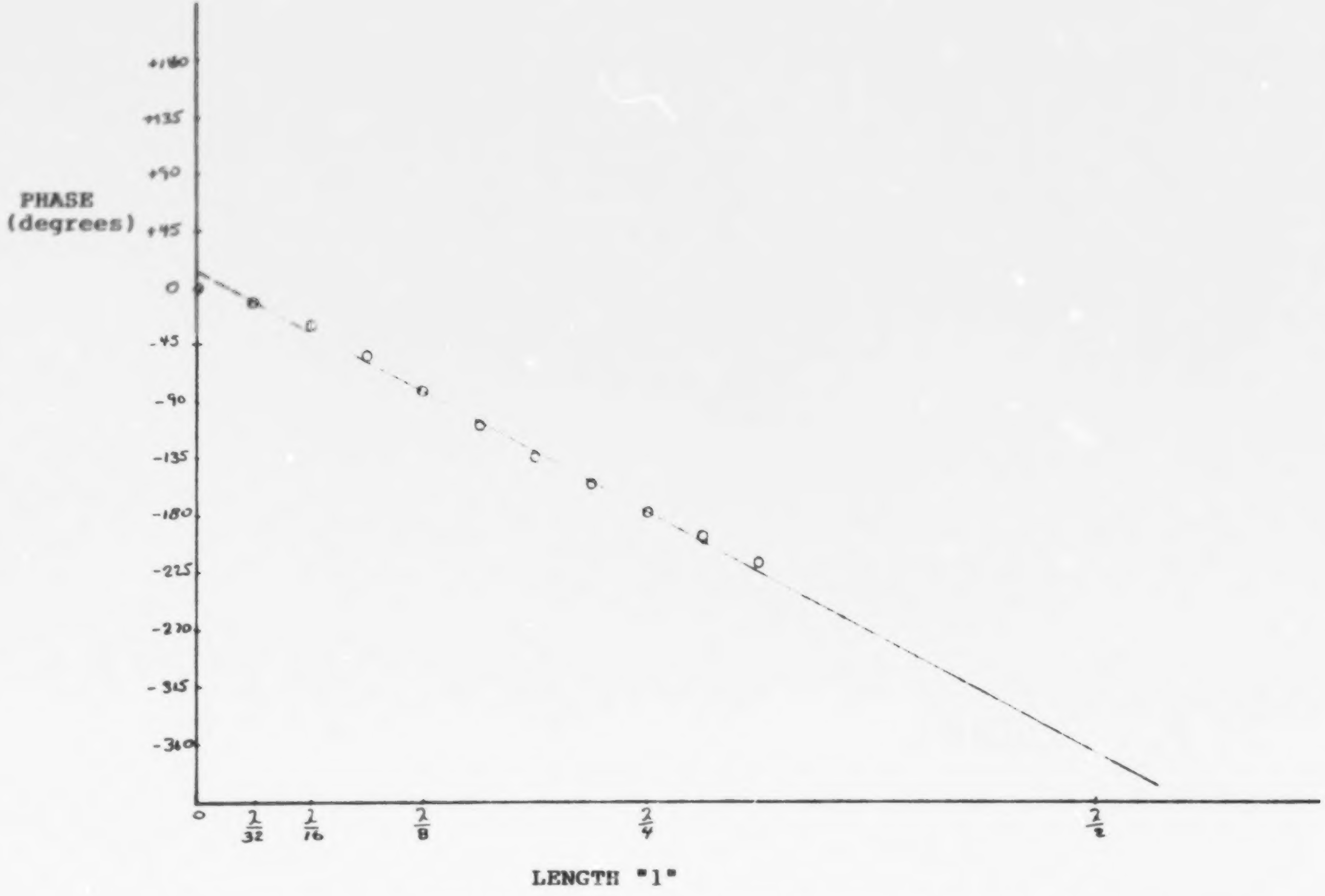


Figure 26 Reflection Port Phase Versus Length of Microstrip Line

From equation 3.10 we get,

$$|\Gamma| = \sqrt{\frac{\left[(R_S - Z_0)(R_S + Z_0) + (wL_S - \frac{1}{wC_J} - \frac{1}{wC_S})^2\right]^2 + \left[2Z_0(wL_S - \frac{1}{wC_J} - \frac{1}{wC_J})\right]^2}{(R_S + Z_0)^2 + (wL_S - \frac{1}{wC_J} - \frac{1}{wC_S})^2}}$$

$|\Gamma|$

— $C_J = .15$ pF, $Z_0 = 50\ \Omega$, $R_S = 1.0\ \Omega$, $L_S = 34$ nH

Therefore

$$\left| wL_S \right| = 10.8\ \Omega, \quad \left| \frac{1}{wC_J} \right| = 209.7\ \Omega$$

for $\underline{\phi = 22.5^\circ}$

$$\ell = \frac{7}{10} \cdot \frac{\lambda}{16}$$

Therefore

$$C_S = .01603 \text{ pf}$$

$$|\Gamma|_{OFF} = 1.0000$$

$$|\Gamma|_{ON} = .996697$$

$$\therefore \Delta |\Gamma| = -.0287 \text{ dB}$$

for $\underline{\phi = 45.0^\circ}$

$$\ell = \frac{12}{20} \cdot \frac{\lambda}{4}$$

Therefore

$$C_S = .02896 \text{ pf}$$

$$|\Gamma|_{OFF} = 1.000$$

$$|\Gamma|_{ON} = .990175$$

$$\therefore \Delta |\Gamma| = -.08576 \text{ dB}$$

for $\underline{\phi = 90.0^\circ}$

$$\ell = \frac{22}{40} \cdot \frac{\lambda}{4}$$

Therefore

$$C_S = .07366 \text{ pF}$$

$$|\Gamma|_{OFF} = 1.0000$$

$$|\Gamma|_{ON} = .97199$$

$$\therefore \Delta |\Gamma| = -.24672 \text{ dB}$$

for $\underline{\phi = 180^\circ}$

$$\ell = \frac{\lambda}{4}$$

Therefore

$$C_S = \infty$$

$$|\Gamma|_{OFF} = 1.000$$

$$|\Gamma|_{ON} = .96253$$

$$\therefore \Delta |\Gamma| = -.33173 \text{ dB}$$

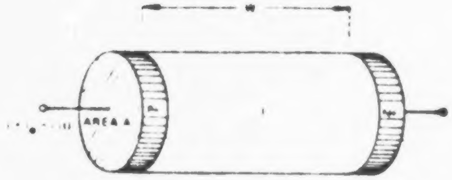
Total Δ Insertion loss = −.6929 dB

The system specifications required a delta insertion loss of 0.50 dB and an RMS phase error of 4 degrees. With the given design one will achieve 0.70 dB insertion loss and a RMS phase error of better than 2.0 degrees neglecting manufacturing errors. This tradeoff was found to provide excellent system performance.

PIN DIODES

A description of the pin diode , useful for describing its microwave behaviour, is shown in Fig. 27. The model consists of three zones in a single silicon chip. Heavily doped p+ and n+ regions are separated by a high resistivity intrinsic I region. At room temperature nearly all impurity atoms are ionized; p+ acceptor atoms donate holes and n+ donors furnish electrons to the crystal. With random thermal motion, electrons and holes tend to diffuse into the high resistivity intrinsic I region. However, before carriers diffuse very far into the I region, the space charge which is built up as a result of these charges moving away from their ionized donor or acceptor atoms prevents further diffusion. Thus, with zero applied bias, the pin diode is essentially nonconducting both to low frequency as well as microwave signals.

With the application of forward bias, the space charge potential's effect is reduced and these charges flood into the I region where they modulate the conductivity making the I region a conductor. However holes and electrons recombine with each other resulting in carrier death. Due to



I_0 = BIAS CURRENT
q = CHARGE ON ELECTRON
p = HOLE DENSITY
n = ELECTRON DENSITY
ρ = $p + n$ BY ASSUMPTION $p = n$, $\rho = 2n$
τ = AVERAGE CARRIER LIFETIME
μ = AVERAGE CARRIER MOBILITY
R = MICROWAVE RESISTANCE OF I REGION

$$I_0 = \frac{qpAW}{\tau} = \frac{qnAW}{\tau} = \frac{1}{2}\frac{q\rho AW}{\tau}$$

$$R = \frac{W}{q\rho\mu A}$$

$$R = \frac{W^2}{2I_0\tau\mu}$$

EXAMPLE
W = 4 MILS = 0.01 CM
I_0 = 0.1 AMPERES = FORWARD BIAS CURRENT
τ = 5 μsec
μ = 1000 cm²/VOLT SEC

$$R = \frac{10^{-4}\ \mathrm{cm}^2}{2 \times 0.1a \times 5 \times 10^{-6}\ \mathrm{sec} \times 10^{3}\ \mathrm{cm}^2/\mathrm{V\ SEC}} = 0.1\,\Omega$$

Figure 27 Forward Biased Diode Resistance Model

recombination, it is necessary to supply a forward bias current to replace lost mobile I region charge if the pin diode is to be kept in a conducting state. The larger the lifetime, the less bias current is required to maintain a given charge distribution in the I region of the diode.

PIN Diode Equivalent Circuit

Figure 28 shows the equivalent circuit for a reverse biased pin diode. From this, one can observe that under forward bias the total resistance between terminals will depend on the doping of the intrinsic region plus that due to the ohmic contacts.

Switching Speed

The pin diode is essentially a capacitor between whose plates a conducting plasma made up of holes and electrons can be injected. This plasma is initiated through the forward bias current. It must be maintained by the application of a continuous bias current because the holes and electrons are continuously recombining. The relationship between the bias current and the recombination is shown in Figure 27. The charge Q stored in the I region, is given by $Q = I_0$. The switching time of the pin is determined by the transition from forward to reverse bias. At this time, the charge Q must be extracted by a momentary current surge provided by the reverse bias supply. Since current multiplied by time equals charge, the time required to withdraw the forward bias charge

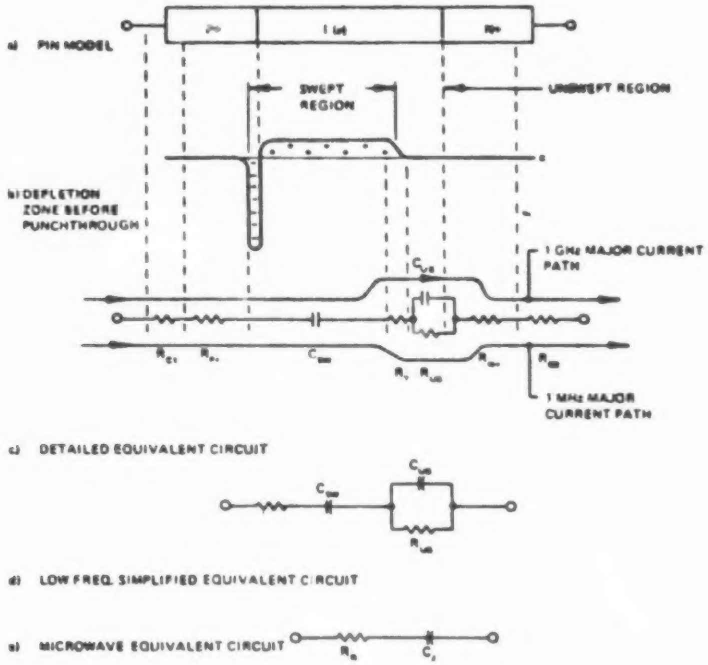

a) PIN MODEL
I (i)
N+
SWEPT REGION
UNSWEPT REGION
b) DEPLETION ZONE BEFORE PUNCHTHROUGH
1 GHz MAJOR CURRENT PATH
C_{UD}
R_{C1}
C_{SW}
R_V
R_{UD}
R_{N+}
1 MHz MAJOR CURRENT PATH
c) DETAILED EQUIVALENT CIRCUIT
C_{UD}
C_{SW}
R_{UD}
d) LOW FREQ. SIMPLIFIED EQUIVALENT CIRCUIT
e) MICROWAVE EQUIVALENT CIRCUIT
R_S
C_J

Figure 28 Reverse Bias Pin Equivalent Circuit

is given by:

$$\tau_s \approx \frac{I_o \tau}{I_r}$$

where τ_s is a switching time and I_r is the average magnitude of the surge of current down from the reverse bias power supply during the transition from forward to reverse bias.

PIN Diode Requirements

At microwave frequencies diode series resistance R_s becomes very important as it directly affects the change in insertion loss as phase bits are switched ON. R_s should be as low as possible in the diode selected for use as increased R_s means increased RF power loss as the diode is turned on. A wide variance in R_s between diodes will unbalance the hybrid coupler causing additional deterioration of phase shifter performance. As previously stated junction capacitance, C_j, must also be closely controlled.

The specifications of the Microwave Associates MA-4P303 diode used are given in Table 7.

Table 7 MA - 4P303 Diode Specification

Breakdown Voltage	200V at 10 Micro amps min.
Junction Capacitance	0.15 pF max at -10 Volts
Series Resistance	1.5 ohm max at 10 ma.
Carrier Lifetime (TL)	0.200 uSec.
Typical Switching time	65 nSec.
Thermal Resistance	30^{o} C/W (max)
Power Dissipation	5.0 W (max)
Case Style	134
Dimemsions	(0.343 mm x 0.419 mm)Typical
Cathode Base	

The choice of diode packaging was based on a need for design predictability. At the frequencies of concern in this project the packaging of the diode introduces unpredictable parasitic effects of capecitance, inductance and resistance. It was desirable to use a diode package which would minimize those parasitic effects so that the development process could more easily concentrate on the design. Dice packaging was used for this reason and all diodes were selected from the same wafer to ensure uniform diode characteristics.

Phase Shifter Design Implementation

The phase shifter will operate over the frequency band 5.030 to 5.090 GHz. At these high frequencies the wavelength of the microwave signal is comparable in size to the dimensions of many of the components used to implement the design. It is important that the reader appreciate the exacting tolerances necessary to successfully translate a design to the physical world. The sections which follow will describe the implementation of the phase shifter design.

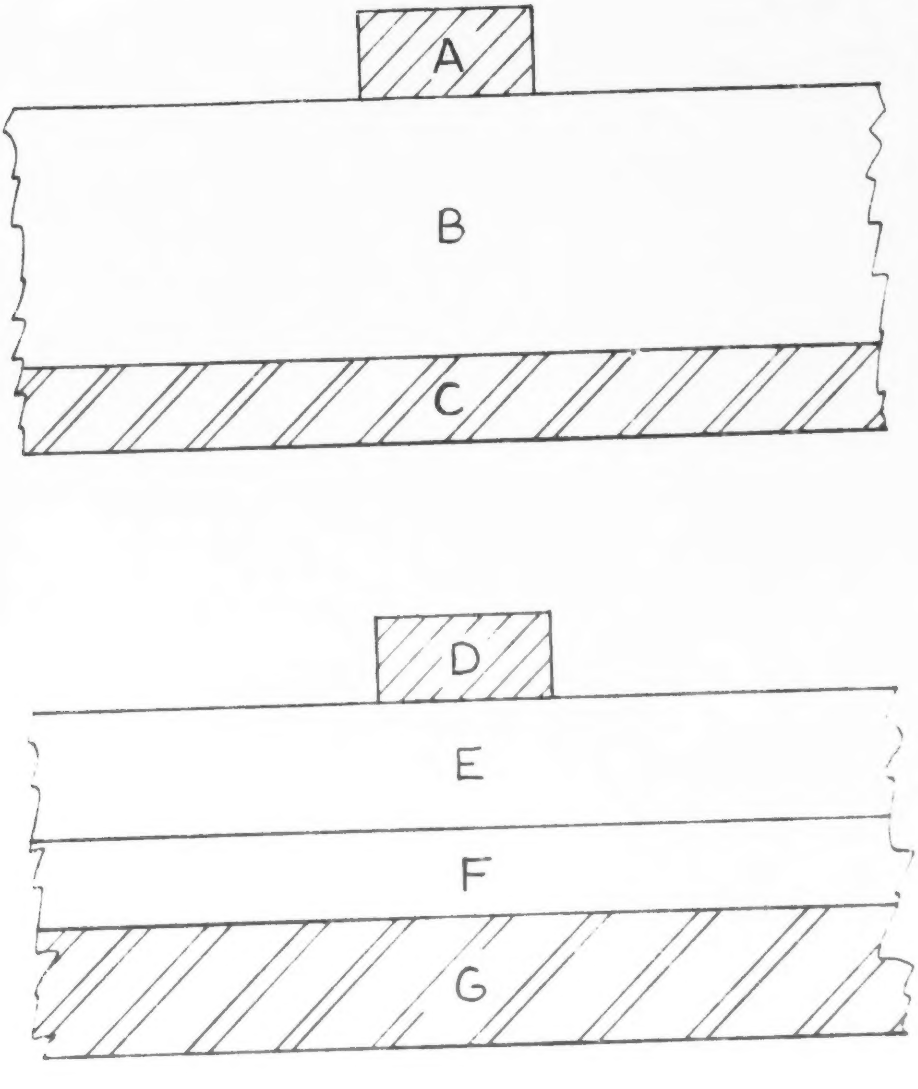
Microstrip Circuit

Microstrip was chosen for the microwave transmission medium. Microstrip designs can be deposited using a sputtering technique allowing the conductors to be defined with high tolerances. A cross section of a typical microstrip line is shown in Figure 29a. The impedance of the transmission line is dependant on the conducting material and its dimensions as well as the dielectric and its dimensions.

Figure 29b shows the cross section of the microstrip circuit actually used in the phase shifters. The copper strip is deposited on a substrate of glass impregnated teflon which is glued to the aluminum base of the phase shifter housing. The glass impregnated teflon and glue make up the dielectric layer, while the alumimum base acts as a conducting ground plane.

The glass impregnated teflon substrate was obtained from Rogers Corp. under the trade name Duriod. Duriod 5880 was chosen over alumina, a popular substrate, because of the following characteristics of Duriod:

1. Low dielectric constant of 2.2 ± .02 providing low



A Conducting strip

B Dielectric

C Conducting plane

D Copper strip

E Glass impregnated Teflon

F 3M Glue

G Aluminium Base

Figure 29 Microstrip Cross Section

loss and good aspect ratios for use with Hybrid coupler design.

2. Duriod is a soft material compared with alumina permitting easy trimming of microstrip lines for tuning purposes.

Great care was taken in the construction process to see that the dielectric constant was consistent over the entire circuit board. This required a constant dielectric thickness. The glue used was a 3M compound mixed to the same dielectric constant as that of the duriod. To maintain an even thickness of glue the aluminum base was machined. The bonded boards were cured at 100° C under pressure to remove any air bubbles in the glue.

As mentioned previously the circuit pattern was deposited on the substrate by use of a sputtering process. The high accuracy of this technique allows the designer to concentrate on problems at the actual circuit design level separately from inaccuracies introduced by a manufacturing process. Sputtering produces a microstrip pattern with extremely straight conductor walls thus allowing exacting dimensional tolerances.

Sputtering is a means of depositing metal on a nonmetallic surface. The technique involves placing a sheet of the nonmetallic substrate in a vacuum along with the metal to be deposited on the surface. A high electrical potential applied to the pure metal causes particles of the metal to be "sputtered" onto the surface of the substrate.

To produce the phase shifter circuit pattern a thin layer of copper is placed on the Duriod using the sputtering method. The board is next coated with photo resist (a light sensitive compound). Exposing the photo resist covered board to ultraviolet light through a photo mask of the microwave circuit will change the characteristics of the exposed areas of photoresist. When washed in solvent the circuit pattern is etched into the photoresist layer Figure 30a.

Copper may now be electroplated to the exposed copper surface as shown in Figure 30b. The excess photoresist is removed (Figure 30c) as well as the thin layer of sputtered copper. A straight-walled copper strip of exact dimensions remains (Figure 30d).

The required height of the microwave conductor is determined by the skin depth of the conductor at the operating frequency. The copper stripline pattern is 5 microns thick allowing for the skin depth plus a safety factor. To protect the copper from deterioration and to facilitate gold wire bonding the circuit lines were gold flashed with about 1 micron of gold.

Diode Mounting

The diodes are mounted to the Duriod after it has been glued to the aluminum housing base. The diode chips are soldered to the copper microstrip by first placing a solder preform on the base of the chip and then allowing the solder to reflow during the mounting process. To improve circuit predictability

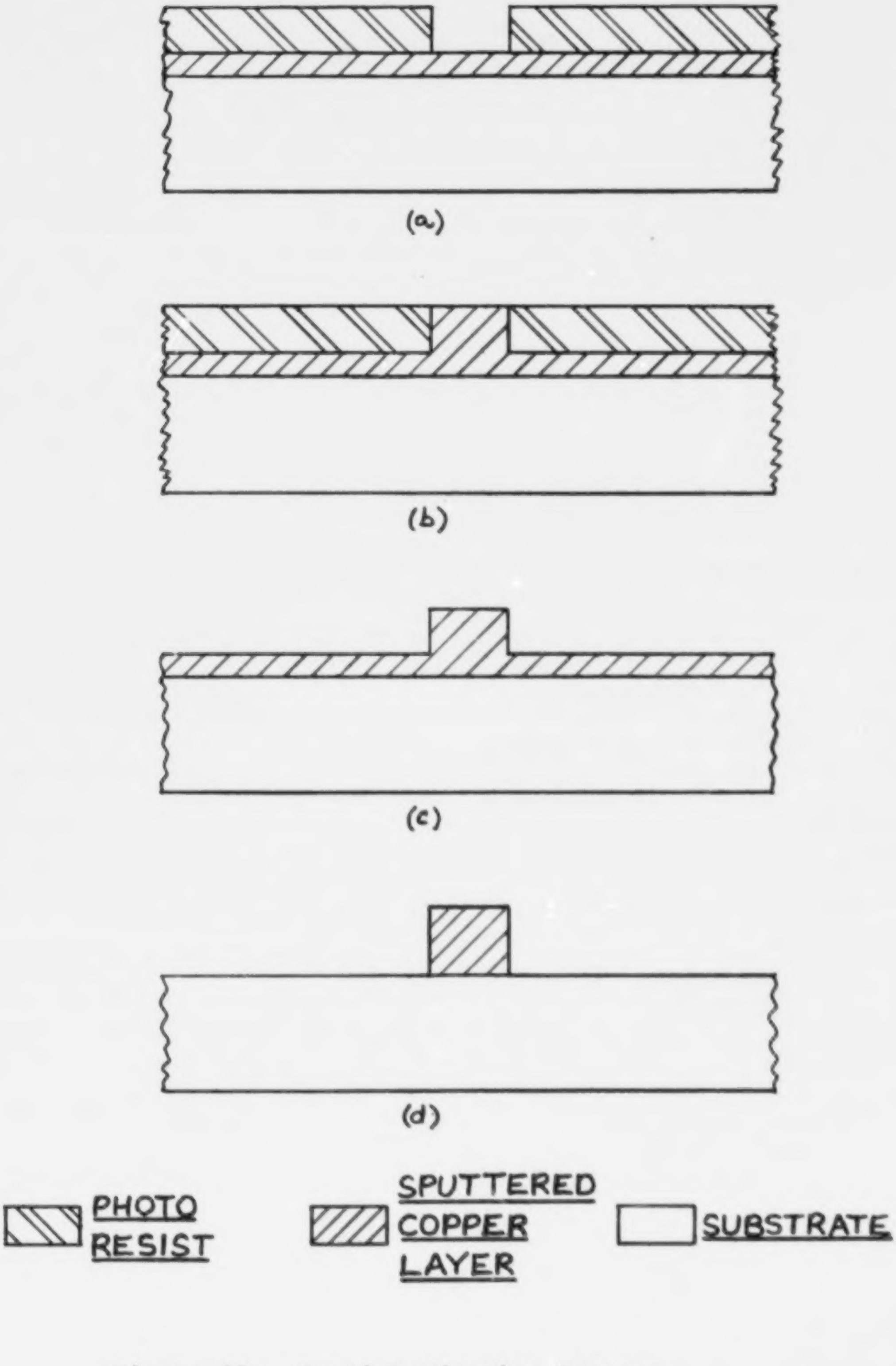

(a)
(b)
(c)
(d)
PHOTO RESIST
SPUTTERED COPPER LAYER
SUBSTRATE

Figure 30 Board Production Process

the diodes were mounted with similar orientation.

The diode anode is connected to the microstrip hybrid circuit using 1.2 mil gold wire. The bonding was accomplished using a combination of ultrasonic and pressure techniques. The bonding wire acts like an inductance at these frequencies. Its length was dependent on the position of the bond, so it was important to bond the wire to the hybrid stub at the same point for all phase shifters. This minimized the amount of trimming needed to produce the correct phase shift for each bit.

Microwave and Bias Connectors

Four bias lines and one bias return line are brought on board using a ribbon cable and ribbon cable connector. The bias lines must be connected to the diodes in a manner that does not effect the operation of the hybrid. This is accomplished by using narrow lines that are high impedance at microwave frequencies but are good conductors at D.C.

OSP type connectors were used for the microwave input and output. These connectors are manufactured by Omni-Spectra; Part #4557-1154-02. OSP connectors are of the "plug in" variety allowing for quick connect and disconnect. A low VSWR and good mating characteristics make them suitable for the phase shifter.

To accomplish a good match between the OSP connector and the microstrip circuit, it is critical that the substrate mate flush with the edge of the OSP connector and the housing side wall. If there is a gap the impedance characteristics will be altered resulting in reflections. The OSP centre pin is soldered to the microstrip.

Phase Shifter Operational Description

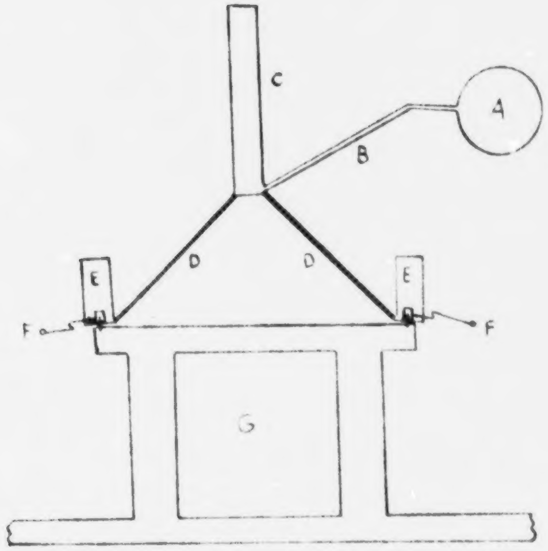
One hybrid bit of the four bit phase shifter is shown in Figure 31.

The phase shift of the hybrid circuit results from the switching of reactances into the circuit by the diodes. When the diodes are turned on (forward Bias) the reactive lines (E in Figure 31) become part of the hybrid circuit causing a change in phase. The amount of phase shift is determined by the length of the reactive lines.

The MLS control electronics determines whether a phase shift section is to be turned on or off; in other words whether the diodes are to be turned on or off. The bias required to turn the diode on is brought to the bias pad (A in Figure 31) by a ribbon cable and connecting wire. The narrow direct current bias lines (C and D Figure 31) present a high impedence to the microwave signals.

Line C of Figure 31 is an open circuited ¼ wavelength line and thus presents a short circuit to any microwave energy present in the bias line D at the frequency of interest.

Bias line D in Figure 31 is also a ¼ wavelength line. This line is terminated by a short circuit. Microwave theory shows that this ¼ wavelength line, terminated with a short circuit,



A	Bias line pad
B	Bias line
C	¼ wavelength open ciruited line
D	¼ wavelength bias line
E	Reactive lines (Tuning Stubs)
F	Diode and Bonding Wire
G	Hybrid

Figure 31 Hybrid Bit

will present an open circuit to a microwave signal present in the reactance line E. These precautions provide very good decoupling of the D.C. bias lines from the microwave signals.

A bias return line also uses a ¼ wavelength line terminated in a short circuit. This presents an open circuit to the microwave signals and a low impedance line to the bias currents. This bias return line was connected to the base using a screw. The screw however caused some radiation of microwave energy requiring absorbant material to be affixed to the phase shifter cover over the screw location.

The schematic of the phase shifter circuit is given in Figure 32. Notice that the corners of the Duriod are mitered to reduce reflections.

Phase Shifter Testing and Trimming

After the phase shifters were fabricated the phase of each bit as well as the overall through phase had to be measured and trimmed.

The measurement of the insertion loss and phase for each state and the input VSWR was done on a Hewelett Packard 8409C automatic network analyzer. The automatic network analyzer or ANA is controlled by a computer. The computer was used to self calibrate the ANA and to read and record the measured data so that it could be processed and displayed in a number of forms.

In order to repeatably measure the phase shifters a test

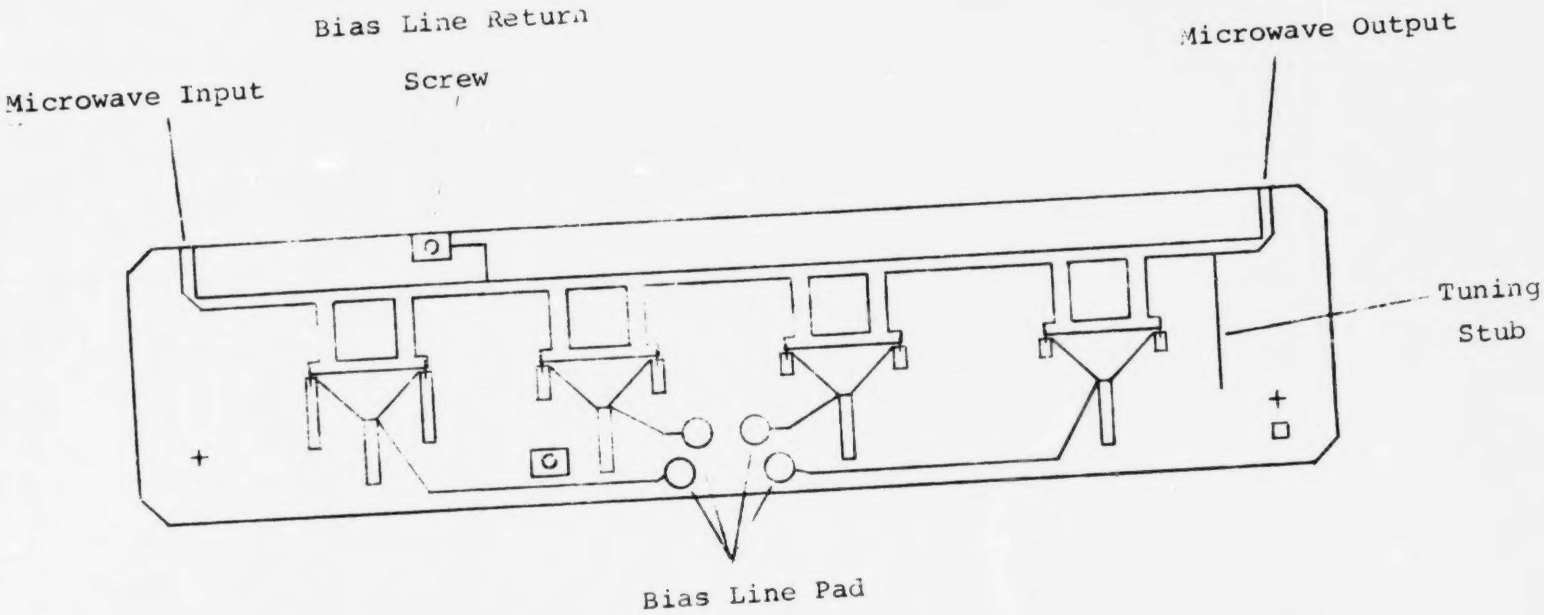

Bias Line Return
Screw
Microwave Input
Microwave Output
Tuning
Stub
Bias Line Pad

Figure 32 4-Bit Phase Shifter

jig was made which firmly clamped the phase shifters into a pair of connectors attached to cables going to the ANA. During self calibration of the ANA the computer records the effect of the test jig. Then when the phase shifters are measured it subtracts the effect of the test jig from the result.

Trimming of the phase shifter tuning stubs is required to obtain the desired phase shift for each bit. Trimming is actually an adjustment of the switchable reactance value which may be inserted in the Hybrid by the diodes.

Trimming was carried out while the phase shifter was connected to the network analyzer. While viewed through a microscope the tuning stubs would be trimmed using an Exacto knife. Using this method a typical trim of one half a thousandth of an inch was possible. If a stub were over trimmed sliver epoxy could be added to the stub to increase its effective length. The epoxy would then have to be cured at 100° C. Trimming could then be repeated but with great care due to the brittleness of the silver epoxy.

To tune the phase shifter for absolute phase a tuning stub was incorporated into the design. This stub is a branch off the phase shifter output line which allows 15° of absolute phase tuning. If a larger phase adjustment is required a small piece of alumina may be placed over the microstrip line to delay the phase.

Phase Shifter Results

The final specifications and test results for the MLS phase shifters are given in Table 8 .

Table 8 Phase Shifter Final Specification and Test Results

Circuit Configuration	4 bit Hybrid Coupled 22.5°, 45°, 90°, 180° sections
Operating Frequency	5.030 to 5.090 GHz
RMS Phase Error	2 Degrees Max RMS, 5.030 to 5.090 GHz
VSWR	1.4 : 1
Delta Insertion loss any state	0.90 dB Max.
Delta Insertion loss between phase shifters	0.5 dB
Insertion Loss	2.4 dB Max.
Switching time	100 ns Max.
Operating temperature range	± 65° C
Driver Requirement per Bit	
Off state	8V reverse bias
On state	40 mA Per Bit

The RMS phase error of 2 degrees **betters** the original design requirement of 4 degrees. This improvement over the original specification was obtained by careful attention to phase shifter tolerances. The delta insertion loss figures were slightly higher than desired but are offset by the reduction in RMS phase error.

There are several areas of the phase shifter design which may benefit from improvement in the final production version.

1. To simplify production a substrate having a metal backing bonded to the substrate may be used. This will eliminate the problems associated with mounting the Duriod to the base of the aluminium housing.
2. A wet etch technique may be used to define the circuit pattern on the Duriod. This method is more cost effective than sputtering.
3. The PIN diode mounting may be accomplished by using silver epoxy rather than solder. This method is simpler and has a lower risk of damaging the diode chip.
4. Trimming of stub lines, needed for phase tuning, will be reduced by improved design. Where trimming is required automated trimming techniques may be utilized to reduce cost and improve accuracy.
5. The bias line return screw connection caused minor radiation problems which will be eliminated by use of an alternate bias ground connection method. The

absorbant material located over the screw on the housing cover will no longer be necessary.

6. The OSP center pin to microstrip solder joints were susceptable to breakage. This is caused by the joints being over stressed when plugged into their mating connectors. Production versions will use a solder jig to pre-stress the OSP connector during the soldering process.
7. The phase shifter housing may be redesigned to reduce its size and cost. The new housing will have as little effect on circuit performance as possible.

Phase shifters which satisfy the MLS antenna requirements have been successfully designed, constructed and tested. The body of knowledge gained through the phase shifter development process will be used to produce production MLS phase shifters.

3.5 The Phased Array

The phased array antenna is composed of 54 slotted waveguide radiators. These radiators are arranged vertically to form the face of the antenna. Each waveguide is excited by the output of its corresponding phase shifter.

The antenna array must provide a narrow, two degree beam which can be scanned horizontally over the area shown in Figure 33. The shape of the beam in the elevation plane must conform to the coverage requirements shown in Figure 34. The type of radiating element was selected and then designed to meet the required elevation plane pattern. The number of elements and spacing between elements were chosen to meet the horizontal plane requirements.

The Phased Array Design

The phased array consists of an array of line source radiating elements. The radiating elements are designed so that when the individual radiation patterns of all the elements are added vectorally, the resultant radiation pattern will be of the desired shape and characteristics. The phased array may be configured by the following means:

1. Stripline dipoles
2. Slotted waveguide elements

Slotted waveguide arrays have the advantages of being compact, rugged, of low insertion loss and low temperature sensitivity. Although the costs of milling slotted waveguides

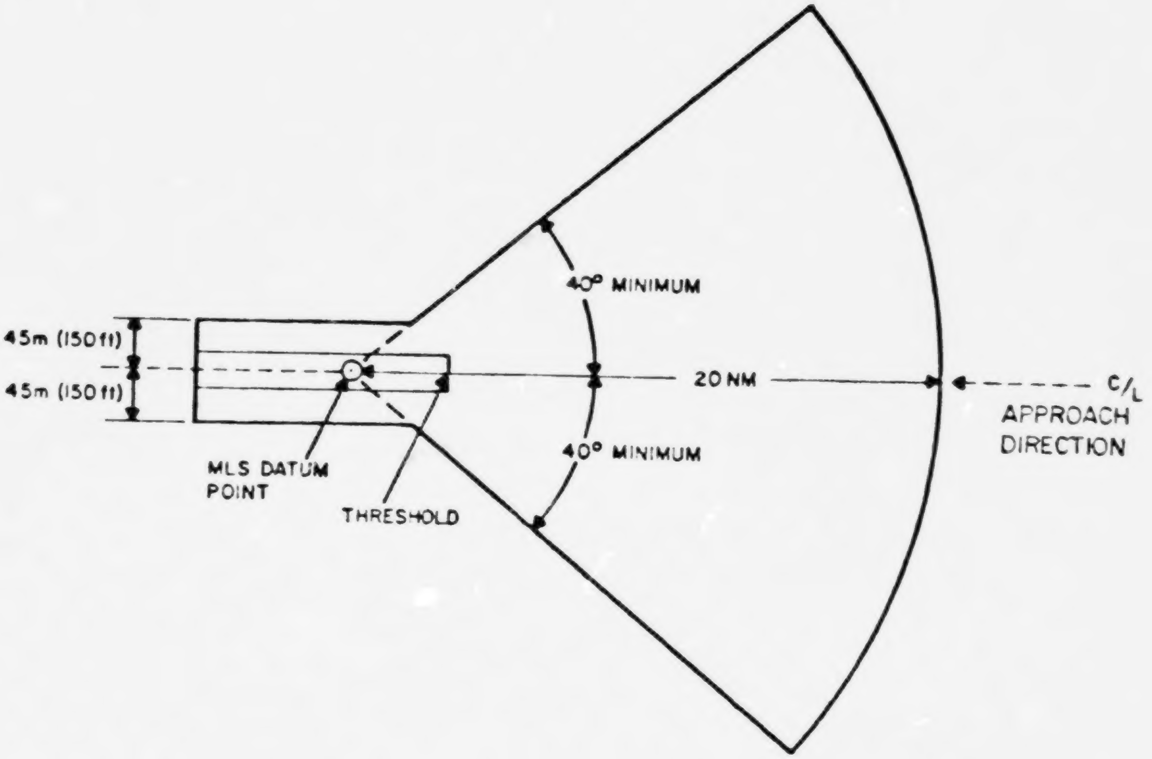

45m (150 ft)
45m (150 ft)
40° MINIMUM
20 NM
40° MINIMUM
C/L
APPROACH DIRECTION
MLS DATUM POINT
THRESHOLD

Figure 33 Azimuth Horizontal Coverage

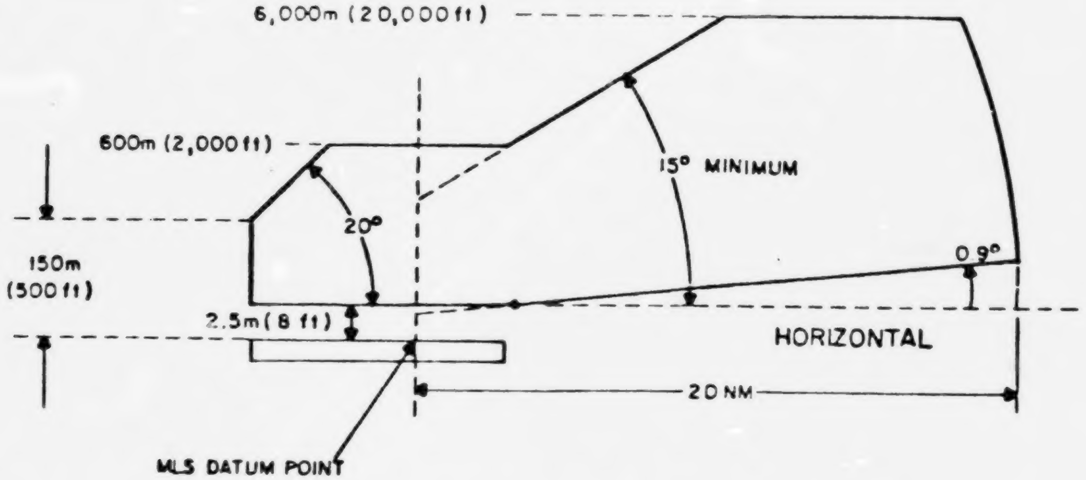

6,000m (20,000 ft)
600m (2,000 ft)
15° MINIMUM
20°
150m (500 ft)
0.9°
2.5m (8 ft)
HORIZONTAL
20 NM
MLS DATUM POINT

Figure 34 Azimuth Vertical Coverage

is greater than the cost of etching stripline circuits, the slotted waveguide does not require the expensive packaging needed for stripline and is a more established technology. For these reasons a slotted waveguide array was selected.

A slotted waveguide is as the name inplies simply a length of waveguide channel with slots cut in the channel to permit electromagnetic radiation. The position, angle and number of slots determines the radiation pattern of the particular slotted waveguide element for a specific input (phase, amplitude and frequency). Two slotted waveguide design techniques may be used:

1. Nonresonant edgewall slots with uniform slot spacing. Phase is controlled by varying the slot length and amplitude is controlled by varying the slot angle.
2. Resonant edgewall slots with nonuniform slot spacing. Phase is dependent on slot spacing and amplitude is dependent on slot angle.

If the phasing requirements can be satisfied by nonuniform slot spacing the design will be less complex than uniform slot spacing. The method of resonant edgewall slots with nonuniform slot spacing was used.

Radiation Pattern

To satisfy the azimuth radiation pattern requirements the following design considerations must be addressed:

a. Number of elements - larger numbers of radiating elements increase the system cost.

b. Spacing of the elements.

c. Individual element radiation pattern.

d. Mutual coupling between elements.

e. Amplitude and phase excitation of the elements.

A 30 dB design sidelobe level was chosen as the antenna specification. This permits a safety margin of 7 db over the actual system requirements. This safety margin is needed to allow for design approximations and construction limitations. A Taylor design yields a pattern that provides optimum compromise between beamwidth and sidelobe level.

For a Taylor distribution the -3 dB beamwidth is given by

$$\text{Beam Width} = 2 \text{ arc Sin } \left(\frac{\lambda \sigma \beta_0}{2L}\right) \tag{3.15}$$

The parameter $\bar{n}$ is a constant chosen by the designer with respect to a desired sidelobe level.

For a -30 dB $\bar{n} = 4$ Taylor distribution

$\sigma = 1.06934$ scaling factor

$\beta_o = 1.057$ constant determined from sidelobe level

L = line source dimension

$\lambda = 0.059$ m wavelength

Substituting and solving for L Beamwidth = 2°

$$L = \frac{\lambda \sigma \beta_o}{2 \sin \frac{\text{Beamwidth}}{2}} = 1.920 \text{ meters}$$

System cost increases as the **number of waveguide elements** increases. Therfore we wish to minimize the number of radiating elements.

For maximum scan angle of θ_m with a spacing of "d" between elements the phase shift ϕ between elements is given by

$$\phi_m = \frac{2\pi d \sin \theta_m}{\lambda} \tag{3.16}$$

The phase shift will cause a grating lobe if the element separation (d) is to great. The angle of the grating lobe θ_G is given by:

$$\frac{2\pi d \sin\theta_G}{\lambda} + \phi = 2n\pi \quad (n=1,2,3....) \qquad (3.17)$$

It is desirable to locate the first grating lobe at the null of the element pattern (90°) for the maximum scan angle,

$$\frac{2\pi d}{\lambda} + \phi_m = 2\pi$$

Substituting in (3.16) gives

$$2\pi - \frac{2\pi nd}{\lambda} = \frac{2\pi nd \sin\theta_m}{\lambda}, \quad \theta_m = 40^\circ$$

$$= 3.609 \qquad (3.18)$$

The aperature had been found to be 1.920 meters. With a spacing of 3.609 centimeters the array requires 54 elements.

Using the standard Taylor formula (3.15) the relative amplitude excitation values for each radiating element are given in Table 9.

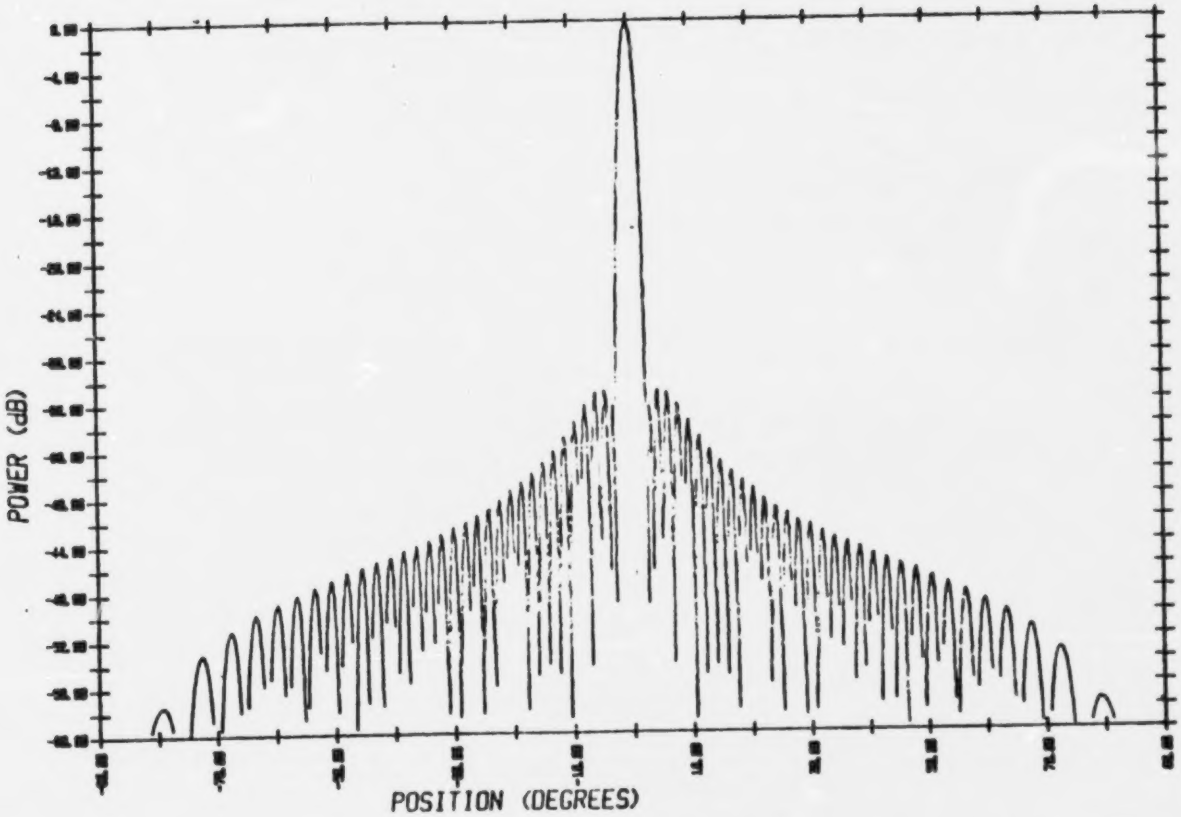
The theoretical radiation pattern for the phased array antenna, with zero phase gradient, is given in Figure 35.

Table 9 Azimuth Amplitude Values

Number of Elements= 54

Initial Spacing= .611 Wavelength

Element No.	Amplitude	Element No.	Amplitude
1	.379	28	1.556
2	.386	29	1.550
3	.402	30	1.536
4	.427	31	1.514
5	.460	32	1.487
6	.505	33	1.455
7	.556	34	1.416
8	.612	35	1.370
9	.673	36	1.321
10	.739	37	1.267
11	.807	38	1.209
12	.876	39	1.146
13	.946	40	1.081
14	1.014	41	1.014
15	1.081	42	.946
16	1.146	43	.876
17	1.209	44	.807
18	1.267	45	.739
19	1.321	46	.673
20	1.370	47	.612
21	1.416	48	.556
22	1.455	49	.505
23	1.487	50	.460
24	1.514	51	.427
25	1.536	52	.402
26	1.550	53	.386
27	1.556	54	.379



54 ELEMENTS, .611 LAMBDA SPACING, TAYLOR DISTRIBUTION, N=4, 30 dB SB

Figure 35 Azimuth Antenna Pattern

Synthesis is the process of translating a theoretical antenna design to a set of physical and electrical antenna parameters. The overall radiation pattern is the vector sum of the radiation patterns of the individual radiating elements. Suitable phasing of the radiating element excitation makes it possible to radiate the antenna beam in a desired direction.

The required radiation pattern for the MLS azimuth antenna in the elevation is given in Figure 36.

The Woodward antenna pattern synthesis was used for beam shaping. The synthesis is accomplished by sampling the desired pattern at various descrete locations. The number and amplitude of the sampling points is varied to optimize the fit of the radiation pattern. The Woodward synthesis method reconstructs patterns whose values at the sampled points are identical to the ones of the desired pattern.

The synthesis will result in a slotted waveguide radiation pattern such that the phase of the individual patterns will have common phase in the centre of the far field thus providing maximum amplitude at this point. Left and right of centre the individual radiator patterns will tend to cancel resulting in lower amplitudes in the sidelobes.

Using the Woodward synthesis the far field radiation pattern may be defined at the angles given by:

$$\Theta = \sin^{-1}\left(\frac{\lambda u}{L}\right) \quad \text{where} \quad u = 0, \pm 1, \pm 2 \ldots$$

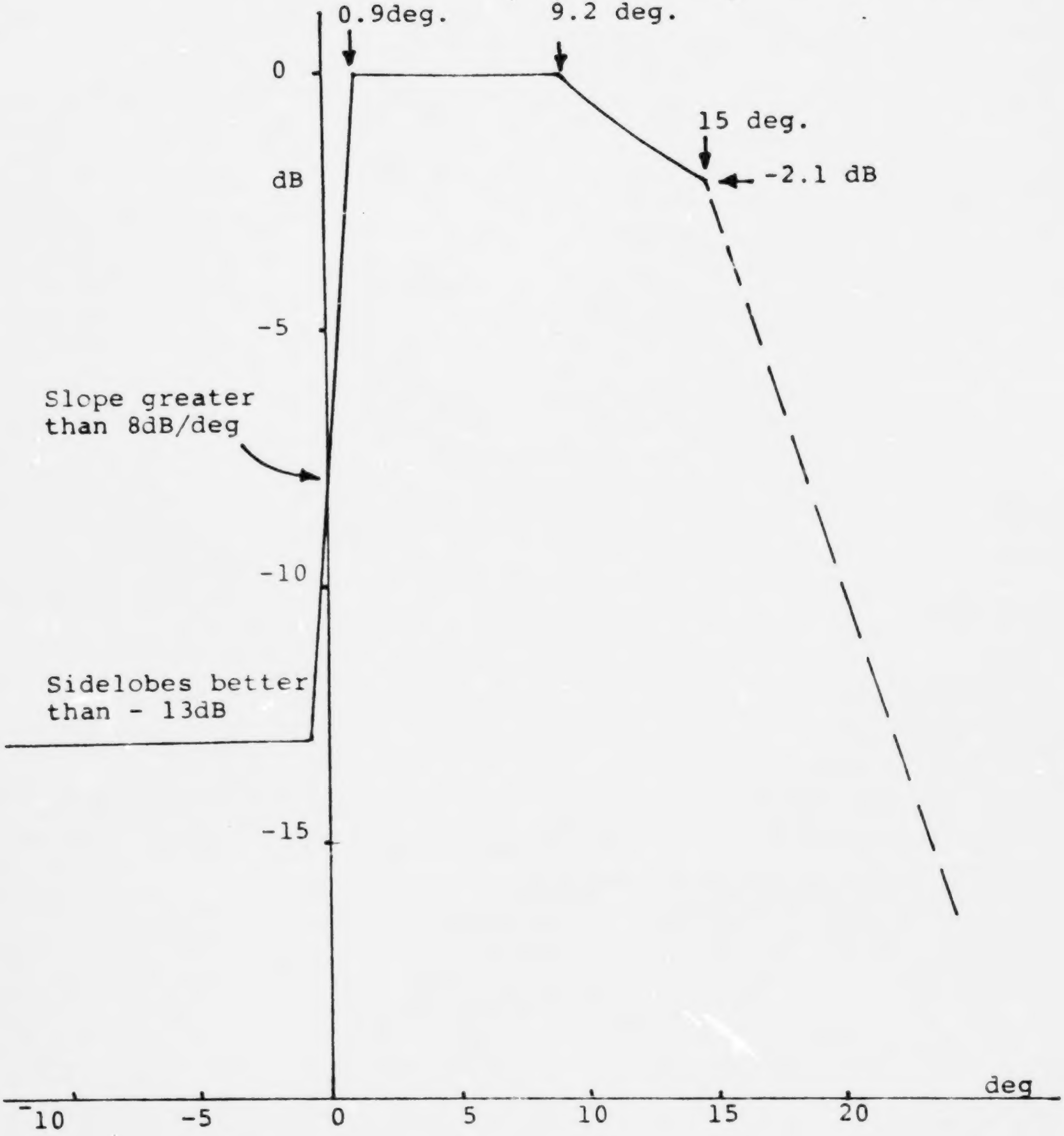


Figure 36 Required Elevation Plane Radiation Pattern

This is equivalent to assumming a $\sin\frac{u}{n}$ radiation pattern centered at these angles. Each of these patterns is produced by a uniform amplitude distribution with the corresponding phase slope. By summing all these distributions it is possible to realize the overall required radiation pattern. The synthesized pattern is shown in Figure 37.

Waveguide Elements

Slots may be cut in the waveguide in a variety of positions. However, to obtain vertical polarization from a vertically mounted waveguide, the edge slot is most suitable. The narrow dimension is less than half a wavelength in free space, therefore the slot is wrapped around the broadside to achieve the length required for resonance. Refer to Figure 38.

Each slot radiates a portion of the waveguide signal dependent upon the slot angle. Figure 39 shows the relation between conductance and slot angle. The resonant conductance of an edge slot may be expressed as:

$$G = G_o \sin^2 \theta \qquad \text{for } \theta < 15 \text{ deg}$$

The value of G_o is dependent upon waveguide dimensions, the frequency and the slot depth. Figure 40 shows a typical variation of G_o versus slot depth. The slotted waveguide design is achieved by measuring a test slot for a particular waveguide over a given frequency band. Using these results G_o is determined.

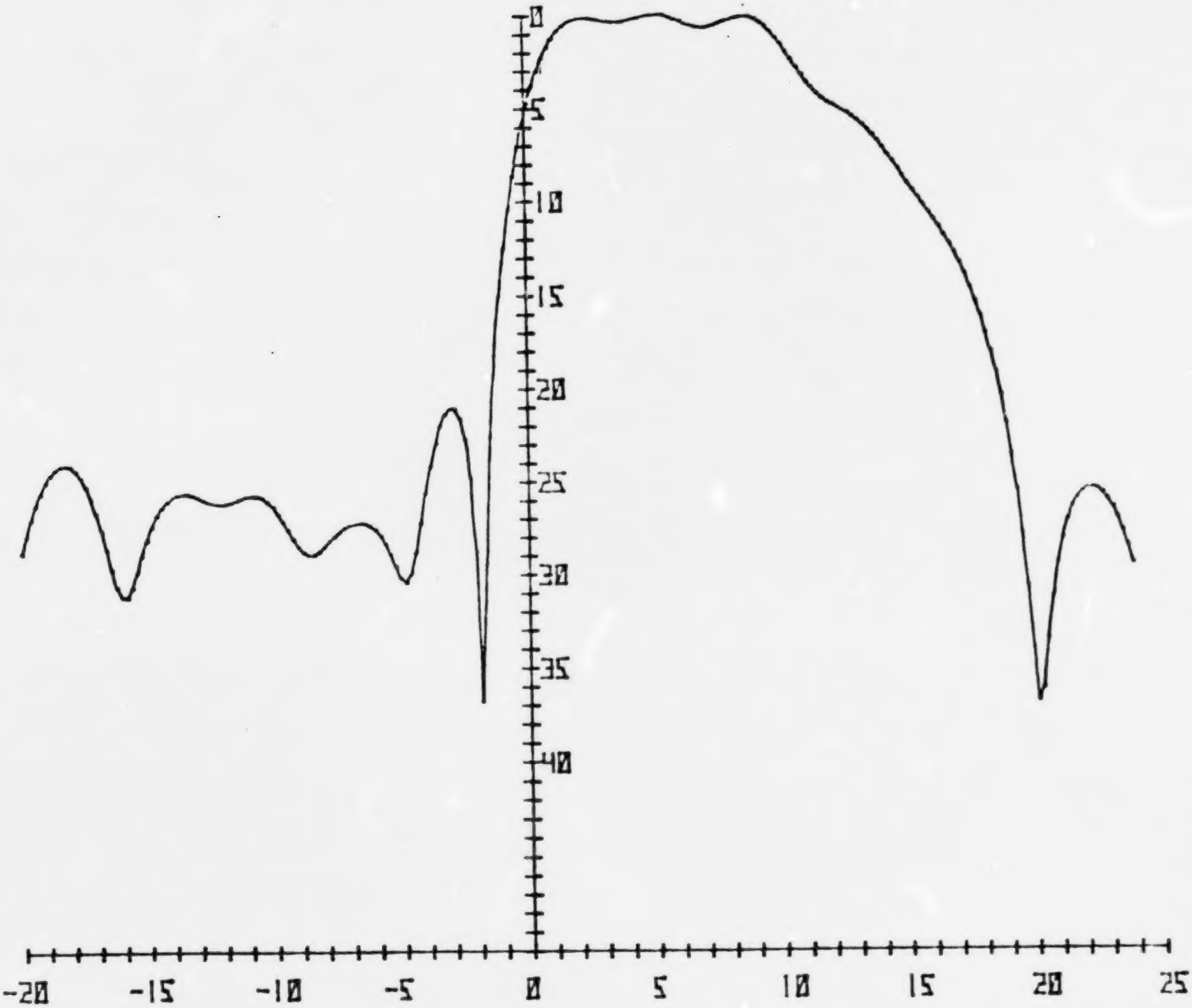


Figure 37   Synthesized Radiation Pattern

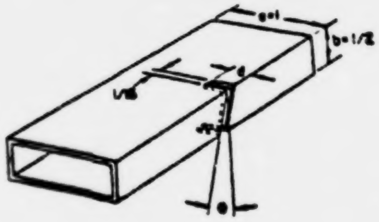


Figure 38 Edge Slot in Rectangular Waveguide

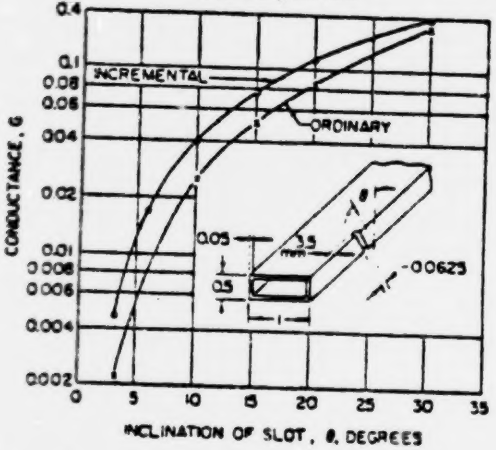


Figure 39 Incremental and Single-Slot Conductance

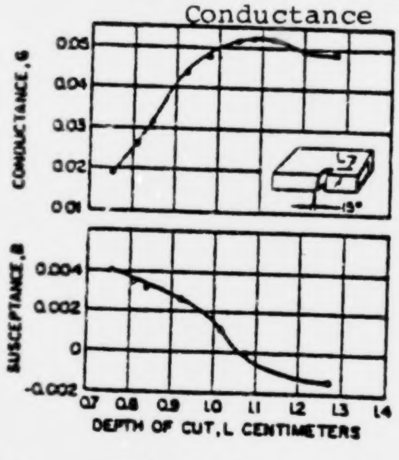


Figure 40 Variation of Slot Admittance with Dept of Cut

Because the slots in a slotted waveguide are placed at an angle with respect to the horizontal, a significant level of cross polar energy **is** produced. A major portion of this can be cancelled, by having the slots in a waveguide with inclinations in opposite directions on alternate slots.

Component Realization

a. Slotted Waveguide

The slotted waveguide requires, from design, 36 slots cut at various angles in the edge wall of the waveguide. Shown in Figure 41 is the slot angle and its distance down the waveguide. The machining of the slotted waveguide is quite a difficult task. The accuracy of positioning the slots as well as the deburring of the slots are factors which can distort the radiation pattern. The slots were cut on a numerically controlled machine so that each waveguide has identical positioning of the slots. Hence the phase of each radiating slot should be identical across the array.

Tests on a slotted waveguide were performed at the David Florida Laboratory in a large anechoic chamber. The slotted waveguide under test was placed in between two other identical slotted waveguides to simulate the mutual coupling that occurs in any array.

Elevation radiation patterns and azimuth radiation patterns as well as cross-polarization patterns were taken in order to determine whether the slotted waveguide characteristics

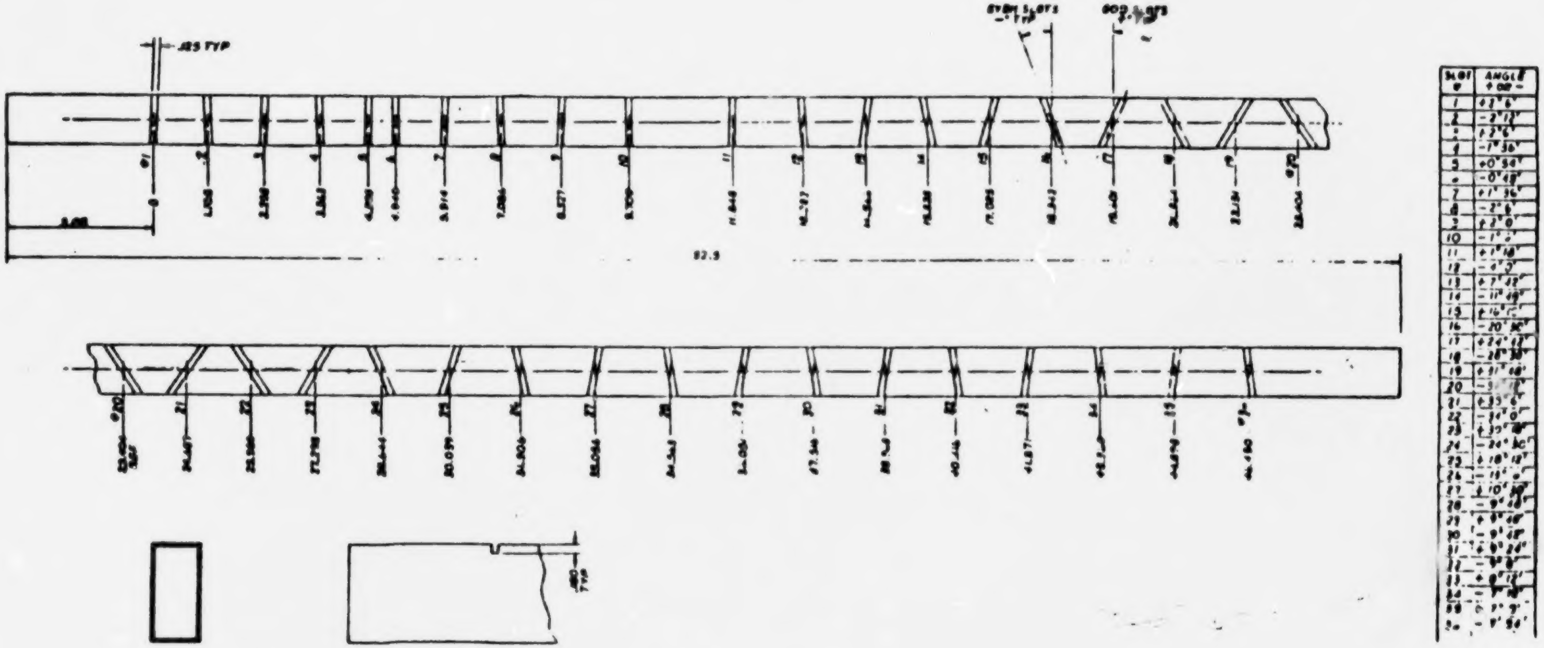


Figure 41 Slotted Waveguide

were acceptable. All patterns were repeated for both ends of the 60 MHz band as well as the center of the band.

b. Coax to Waveguide Transition

For the excitation of our array of rectangular waveguide radiators, an end-launcher transition from coaxial line to rectangular waveguide was used. The transition shown in Figure 42 was used to excite the dominant TE_{10} mode in the rectangular waveguide. Optimum dimensions for the elbow were calculated, and testing determined that a matching screw was necessary to achieve a 30 dB return loss over the 60 MHz bandwidth.

c. Phase Trimming Screws

In order that each slotted waveguide excites power at the same phase across the array, there must be some method for fine tuning the phase of the slotted waveguide assembly. The reason for the errors in phase are due to manufacturing errors and assembly tolerances. A simple technique to tune the phase of each slotted waveguide is to insert two tuning screws, spaced one-quarter of a wavelength apart in the narrow wall of the waveguide. The screws may be represented as an equivalent capacitance in shunt and having two screws one-quarter wavelength apart, the reflection from the first screw will cancel with that of the second screw. An insertion phase adjustment of up to eight degrees has been measured.

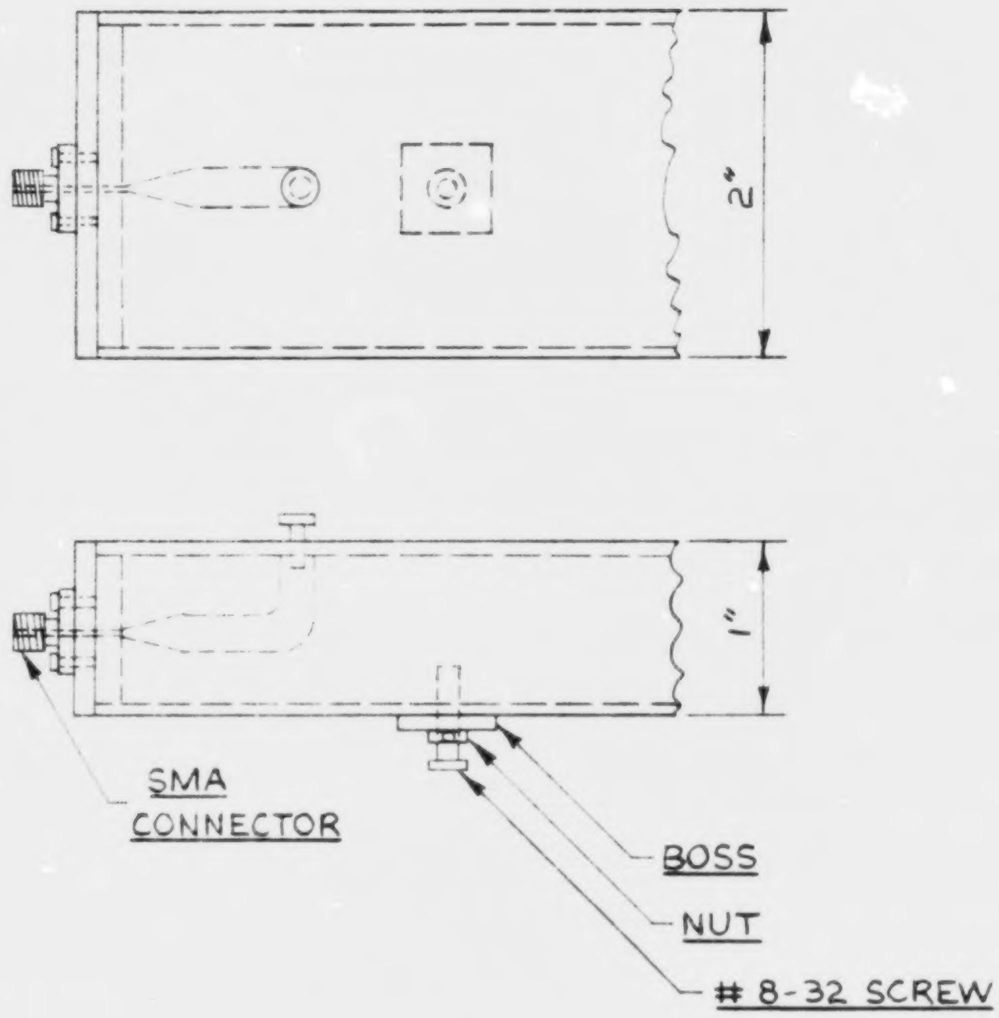

2"
1"
SMA CONNECTOR
BOSS
NUT
# 8-32 SCREW

Figure 42 Coax To Waveguide Transition Assembly

d. Termination

The slotted waveguide design requires the use of a load after the last slot. Because the operation of the array is over a very narrow band, a good matched load is easily obtainable. Ecosorb which is a carbon impregnated ceramic was used in a three step transformer configuration. The return loss was found to be better than 30 dB over the band.

Construction of Waveguide Assembly

The waveguides were constructed of WR187 aluminium waveguide channel. This is a relatively soft and thin material which makes it difficult to machine. Cutting tools must be kept sharp to prevent burrs. A numerically controlled milling machine is used to cut the waveguide slots. Such a machine allows good slot cutting control and improved accuracy because all the waveguide slots are machined in the same pass. The slot edges must be sharp for good coupling and therefore burrs must be carefully removed. The machined waveguide was irridited for corrosion protection. Irriditing is a chromate dip process that leaves a distinctive yellow color on the aluminum.

The launcher section provides a means of transferring microwave excitation in a coaxial line to the waveguide. A SMA type bulkhead connector is used to join the coaxial line to the launcher assembly. The SMA connector cetre pin, is soldered to the launcher probe. The launcher section is then placed in the top of the waveguide (Figure 42) and screwed in place.

The waveguide termination consisted of 2 pieces of Ecosorb positioned in the base of the waveguide.

Bosses to hold tuning screws were machined from aluminium and the areas of the waveguide where the bosses were to be affixed were etched with Hydrochloric Acid to clean the surface and treated with potassium dichromate. The bosses were then epoxied to the waveguide and threads tapped through the boss and into the waveguide wall.

Identical semi-rigid cable assemblies, cut as accurately as possible were attached to the waveguide launcher section. The waveguide assembly was connected to the automatic network analyzer by way of a short section of waveguide with a coaxial connector output which is aligned with the monitor output opening. Four screws were available on each waveguide section for tuning purposes. Two broad wall screws adjust both amplitude and phase. One of these small screws is used for launcher matching, the other is used to correct slot impedance variation due to production. The two other larger screws permit the absolute phase of the slotted waveguide element to be adjusted up to eight degrees. Using the network analyzer the radiating elements are tuned for optimum match and identical phase so that they are interchangeable. The waveguides were now ready for assembly into the antenna system which will be discussed in a later section.

Slotted Waveguide Monitor

The manifold or integral monitor samples the R.F. signal in all waveguides. Outputs of each radiating element are summed to form a composite signal which is analysed by the system electronics to determine the antenna status.

By placing the monitor near the end of each radiating element, all but the terminations of the elements are monitored. A simple monitor is implemented by coupling directly into a waveguide slot near the base of the phased array.

The requirements of the MLS Monitor are:

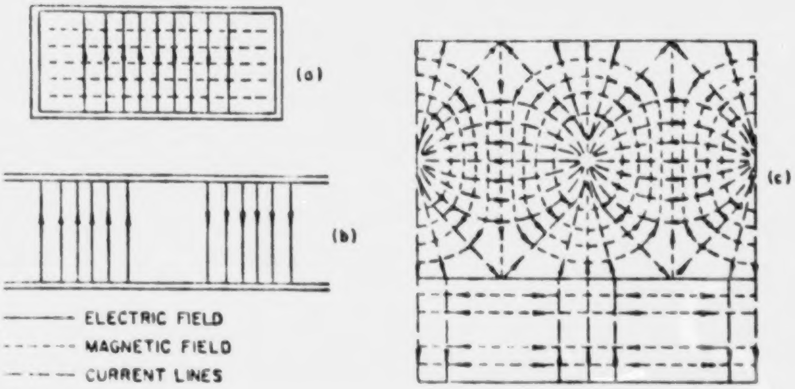
1. The power coupled from each radiating element must be of comparable amplitude to permit a simple set of computations to be used by the microprocessor analyzing the monitor output. To meet this requirement, an inverse Taylor distribution (the complement of the corporate feed output distribution) must be realized by the slot coupling.
2. The coupling outputs must add in phase.
3. The monitor must not alter the slotted waveguide radiation pattern which requires a low coupling value to minimize the effects of signals in the monitor.
4. Monitor coupling mismatch must be minimized.

Figure 43 shows the surface current flow associated with the propagation of the TE_{10} mode in rectangular waveguide. Slots cut in the narrow side of the waveguide wall will disturb the current distribution and "couple" energy from the waveguide. The magnitude of the slot coupling to the waveguide is a function of the component of the slot length perpendicular to the current lines, the current density at the center of the slot, the slot dimensions, the waveguide dimensions, the wavelength wall thickness, and the frequency.

Removing the sidewalls of the array elements permits the flat face of the monitor waveguide to fit flush with the inner face of the array waveguide wall. A slot of less than one half wavelength cut perpendicular to the centerline in the narrow face of the monitor waveguide provides the required coupling with minimum VSWR.

To determine the coupling characteristics and slot length requirements, a test section of monitor waveguide was constructed. The length of the single slot in the test section was varied and its coupling measured using the network analyzer. The results of this testing were used to prepare a graph of coupling versus monitor slot length. The graph, given in Figure 44, was used to determine the slot length corresponding to each waveguide element. Table 10 gives the slot lengths necessary to accomodate inverse Taylor distribution.

A long bed milling machine was required to manufacture the monitor waveguide due to its length. A small diameter


(a)
(b)
(c)
ELECTRIC FIELD
MAGNETIC FIELD
CURRENT LINES

Waveguide Propagating TE$_{10}$ Mode

a) Cross-Sectional View

b) Longitudinal View

c) Surface View

Figure 43 Surface Current Distribution For Rectangular Waveguide Propagating TE$_{10}$ Mode

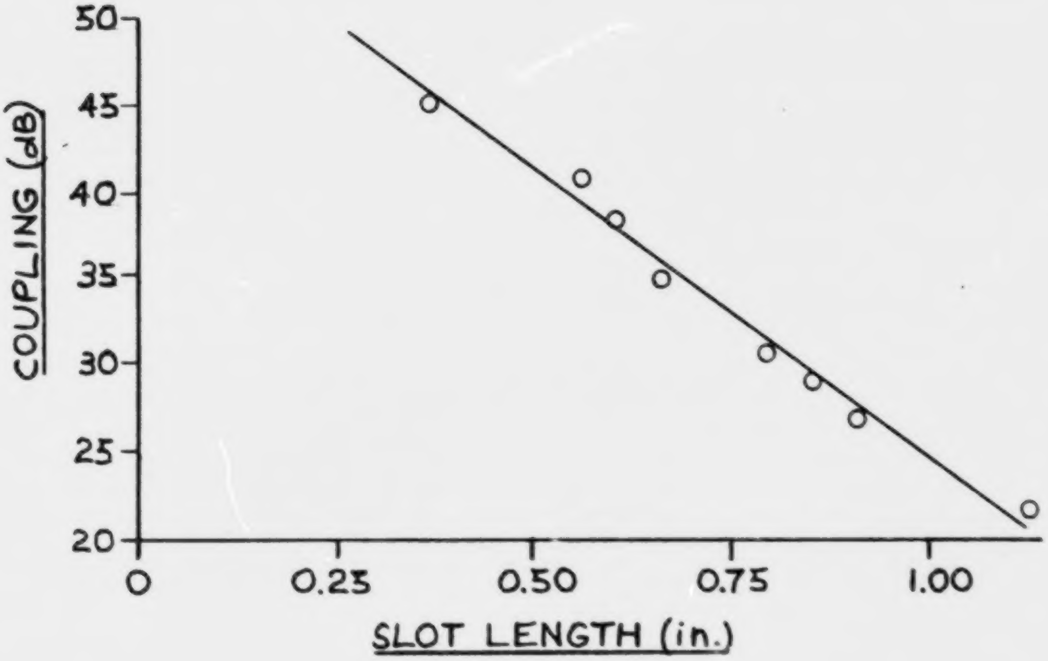


Figure 44 Waveguide Slot Length vs. Coupling

Table 10 Monitor Coupling Dimensions

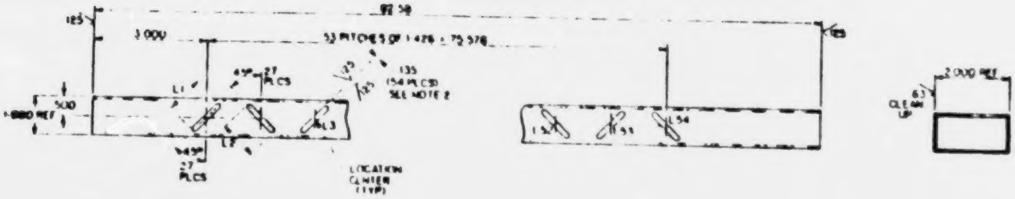
Element	Power (dB)	Coupling (dB)	Length of Slot (in.)
1	0.0	37.28	.600
2	-0.04	37.24	.606
3	-0.12	37.16	.610
4	-0.24	37.04	.614
5	-0.39	36.89	.619
6	-0.59	36.69	.625
7	-0.83	36.45	.631
8	-1.11	36.17	.643
9	-1.43	35.85	.650
10	-1.79	35.49	.663
11	-2.20	35.08	.675
12	-2.66	34.62	.688
13	-3.17	34.11	.700
14	-3.72	33.56	.719
15	-4.34	32.94	.738
16	-5.00	32.28	.756
17	-5.72	31.56	.775
18	-6.48	30.80	.800
19	-7.29	29.99	.819
20	-8.13	29.15	.844
21	-8.98	28.30	.875
22	-9.81	27.47	.894
23	-10.59	26.69	.919
24	-11.28	26.00	.938
25	-11.82	25.46	.956
26	-12.16	25.12	.960
27	-12.28	25.00	.969

cutter was used to cut the slots in position at a 45° angle to the waveguide centerline to provide the correct phase coupling. Burrs were removed from the machined waveguide but edges were left sharp.

The waveguide elements and thus the monitor slots are separated by a distance corresponding to approximately 180° phase difference. Adjacent waveguide slots cut on opposite 45° diagonals are 180° out of phase with each other, which makes the coupled energy of each array element add in phase at scan angle close to 0°. Maximum coupling was limited to 25 db to minimize VSWR and effects on the radiation pattern. A drawing of the monitor is given in Figure 45.

Flanges were mounted on both ends of the monitor. A load is placed in one end and a waveguide to SMA transition is placed in the other.

Initial testing consisted of measuring the coupling of each individual slot using the network analyzer. Further measurements were obtained with the monitor connected to the radiating antenna. The monitor output was observed while each waveguide slot was excited and all other slots terminated. The results of these measurements are given in Table 11. The monitor performed acceptably although the next design iteration could benefit from improved coupling to balance the energy from each element.


125
92.58
3.000
53 PITCHES OF 1.426 = 75.578
125
45°
27 PLCS
L1
L2
L3
135
(54 PLCS)
SEE NOTE 2
.125
.125
.500
1.000 REF
45°
27 PLCS
LOCATION CENTER (TYP)
L52
L53
L54
2.000 REF
63
CLEAN UP

SLOT	DIM	SLOT	DIM	SLOT	DIM
L1	963	L19	650	L37	663
L2	950	L20	643	L38	675
L3	938	L21	631	L39	688
L4	938	L22	625	L40	700
L5	919	L23	619	L41	719
L6	894	L24	614	L42	738
L7	875	L25	610	L43	756
L8	844	L26	606	L44	775
L9	819	L27	600	L45	800
L10	800	L28	600	L46	819
L11	775	L29	606	L47	844
L12	756	L30	610	L48	875
L13	738	L31	614	L49	894
L14	719	L32	619	L50	919
L15	700	L33	625	L51	938
L16	688	L34	631	L52	938
L17	675	L35	643	L53	950
L18	663	L36	650	L54	963

Figure 45   Monitor Waveguide

Table 11 Monitor Distribution (Freq. 5.060 GHz)

Element	**Insertion Loss** (dB)	**Insertion Phase** (DEG)
1	.02	- 0.6
2	- .28	- 14.5
3	- .17	- 17.3
4	.76	- 28.6
5	.90	- 39.3
6	1.99	- 44.0
7	2.33	- 49.5
8	3.13	- 56.7
9	3.64	- 62.8
10	3.99	- 68.7
11	4.86	- 72.5
12	5.80	- 73.4
13	6.90	- 75.9
14	7.93	- 89.5
15	8.05	- 97.2
16	8.44	- 103.3
17	9.38	- 105.6
18	10.19	- 109.3
19	11.13	- 115.5
20	12.39	- 127.1
21	13.48	- 132.2
22	14.63	- 142.9
23	14.33	- 157.2
24	14.70	- 175.2
25	13.79	- 179.9
26	14.09	170.9
27	14.64	163.7
28	14.62	155.8
29	13.70	146.7
30	13.59	129.6
31	13.80	129.0
32	12.66	121.6
33	11.26	114.0
34	10.69	106.6
35	10.42	104.8
36	9.83	109.3
37	9.53	101.3
38	9.11	94.4
39	8.39	90.5
40	7.84	88.7
41	6.36	82.6
42	6.11	78.8
43	5.58	73.4
44	5.19	66.0
45	5.12	59.9
46	4.92	52.2
47	4.19	45.7
48	4.12	34.9
49	3.12	24.2
50	2.65	13.3
51	1.28	4.3
52	0.74	-5.5
53	-0.50	-19.3
54	-1.20	-28.1

3.6 Electronics

The MLS electronics are responsible for timing, control and monitoring functions of the antenna system. A modular approach was used in the electronics design; related functions were grouped together on individual cards.

Timing control and monitoring is performed independently by two identical microprocessor cards or Executive Controller System Monitor (ECSM) cards. The integrity of the timing and control signals is assured by comparing the signals generated by one ECSM with the signals generated by the other. The ECSM's are completely interchangeable in both hardware and software. A third card called the common board contains some of the devices such as comparators, which are shared by both ECSM's.

Since both ECSM's are identical either is capable of controlling the MLS equipment. The selection of which ECSM is in control is performed by the selection logic card. This card will switch control from a malfunctioning ECSM to the functioning unit in the event of a failure. Considerable effort has been made to ensure that a malfunctioning ECSM cannot effect the proper selection of the functioning ECSM.

The steering of the scanning beam is performed by the Beam Steering Logic Unit (BSLU) which controls the phase shifter settings. The BSLU transmits data to the phase shifter driver boards which in turn generate the appropriate bias signals. The bias signals set the state of the diodes in a particular phase shifter. Switching between the on and the off states is accomplished in less than 100 ns.

The drivers are not located in the card rack but are mounted near the phase shifters to minimize the cable runs. The BSLU and driver boards received extensive testing before range tests at David Florida Labs and have shown satisfactory performance in on-line tests with the MLS receiver.

The actual sequencing of the phase shifters is determined by the scan programme which is stored in PROM on the BSLU board. A number of different scan programmes have been tested during static range tests at David Florida Labs and two have been used during field tests with an MLS receiver. Changing the scan programme changes the sidelobe patterns radiated by the antenna. The BSLU also provides for electronic boresighting of the MLS array. Once the array has been mechanically aligned the boresight can be adjusted electronically $\pm 2^{\circ}$ in increments of 0.002°.

An interface card takes the timing signals from the ECSM's and drives the inputs of the microwave source. The signals coming from the interface card control the selection of the ID antenna or the scanning beam antenna, the modulation of the DPSK data, and the switching of the microwave amplifier. The modulator output will perform a gradual (or soft) phase transition using a 4 bit phase shifter. Also included on this card is the voltage regulation required by some of the microwave components and the drivers for the modulating phase shifter.

The Analog board provides monitor inputs to the ECSM's. Information is gathered from the microwave source and antenna monitor and converted to digital data. This data is analyzed independently by each ECSM to determine the system status.

A second level of monitoring is provided by the Equipment Monitor (EQM). The EQM is a separate microprocessor based card which processes the monitored data from the ECSM's. Information on failure history is stored in the EQM for recovery by service technicians. This information is processed to indicate to the technician which card or module has failed. The EQM may sustain a complete failure without affecting the normal operation of the monitor and control electronics.

Each MLS site must be configured for its particular location and function at installation time. The input of such data is performed through the Local Control Status Unit (LCSU). Data can be entered via the keypad on the LCSU or with any terminal using a standard RS232C interface. System responses to commands are displayed in plain English on an alphanumeric display or on the RS232C terminal. This unit is also used to display information on system status and monitored parameters.

The cards that make up the monitor and control electronics are housed in a standard Eurocard rack. The backplane or motherboard for the card rack has been standardized to allow the addition of new cards without any modification to existing hardware. The majority of sockets in the rack are identical so that with a few exceptions the cards can be inserted in any position. All connections between equipment outside the card rack and cards in the rack are made through the motherboard, eliminating the need to have connectors on the front edge of such cards as the BSLU or Interface card. All signals going off and coming on to every card in the rack are buffered using gates with hysterisis on their inputs to give high noise immumity and eliminate any loading problems as more cards are added.

The software operating on the ECSM's has been written to allow all system types (Elevation, Azimuth, or Back Azimuth) to use the same operating system regardless of location. When an MLS is installed the system is configured with the appropriate site specific data through the use of keyboard commands on the LCSU. The data is then protected in non-volatile memory. A hardware switch is used to ensure that any fixed site data cannot be acessed inadvertently.

All operating software is highly modular. Each function has its own module which is further divided into sections and steps. The software documentation consists of a functional description for every module and detailed in - software comments.

4. MECHANICAL DESIGN AND ASSEMBLY

4.1 General

The Microwave Landing System is required to operate on a continuing basis under all weather conditions. Located at the end of runways, on oil rigs, etc., it must provide dependable guidance information from arctic to desert conditions. It therefore must tolerate extreme temperature variations and high winds without any significant degradation of radiated signals. A structure is required which will house and support the waveguide antennas, phase shifters, corporate feed, microwave source, and electronics.

The structure is designed for maximum strength, rigidity and minimum weight. The type of metal to be used must accomodate some important considerations:

a. the structure must protect the internal components
b. it must provide adequate support to prevent deflections of the phased array antenna.
c. thermal stresses must be as low as possible.
d. a relatively simple method of maintenance on internal equipment must be maintained.
e. the entire system must be frangible.

Taking into account these factors, aluminium proved to be the best choice, and also to be cost effective.

4.2 Antenna Support Frame

As described in detail on the following pages, the waveguides, phase shifters, and corporate feed must be located in specific positions for best overall performance. To accomplish such a feat a special antenna frame or support structure is used. It is designed to achieve good mechanical integrity of components in easily maintainable and operational positions.

The structure which is shown in Figure 46 is constructed using a combination of square aluminium tubing, plate, and right angle stock. The tubing is welded together in a wedge shape to inhibit twisting. The rectangular and right angle stock is welded, and placed in the upper rear section of the structure to support the microwave components. The assembly when configured in this manner is reasonably compact. The height is 179.1 centimeters, the width 223.5 centimeters, and the depth is 22.86 centimeters on the bottom.

Two eyelets on top of the support allow easy handling by crane with all the components in place. Mounting bolts and levelling screws are located in the foot plates of the antenna frame. The system is mechanically decoupled from its enclosure whenever possible. The weight of such a structure is approximately 100kg without the components (corporate feed, phase shifters, etc.). With the addition of all components the weight amounts to about 325 kg.

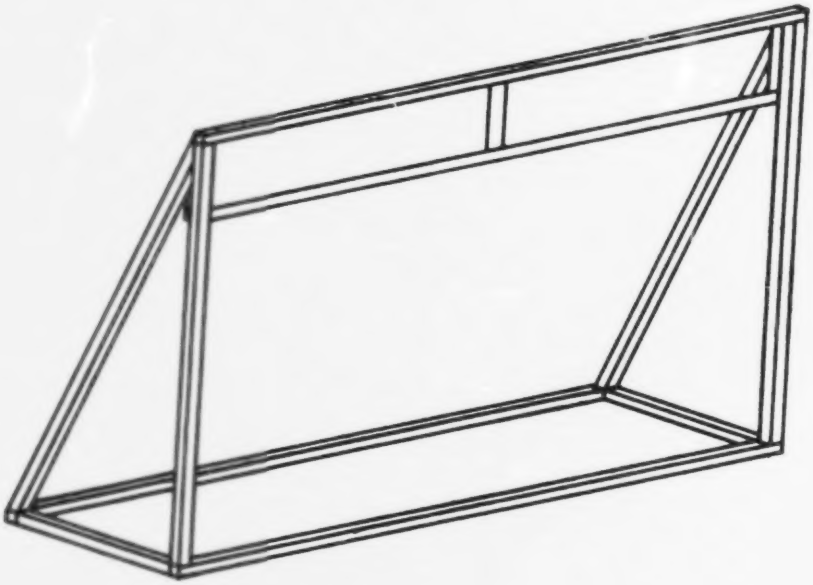


Figure 46 Antenna Support Structure

4.3 Waveguide Assembly Mounting

The vertical waveguide antennas (54 in total) are mounted on the front or vertically straight side of the antenna support. The slotted face of the waveguides are pointed out away from the support structure.

The waveguide assembly can be broken into several modules which are fitted together in the following sequence. The bottom machined waveguide support fits snugly into the end of the waveguide providing a means to bolt the waveguide to the mounting channels and a base to support the termination or load.

The top waveguide support is identical to the bottom waveguide support except it has received additional machining to allow an SMA type bulkhead coaxial connector to be fitted into the piece. This SMA connector is soldered to a launching probe and then inserted into the top of the waveguide and fastened with small screws. A specially designed semi-rigid coaxial cable assembly is attached to this SMA connector. While one end of the cable has the mating SMA cable connector the other has a "floating mount" OSP type bulkhead connector attached.

The coaxial cable is always attached to the SMA connector on the waveguide prior to testing and tuning of the waveguide assembly.

To attach the waveguide assemblies onto the antenna support, four U-bars are bolted on. Two, which are called mounting channels (upper and lower) are fixed to the top and bottom of the structure using stainless steel bolts. All non-weld mounting in the entire system uses stainless steel fasteners. The other mounts called eliminator mounting channels are bolted in the upper middle section in the same plane as the previous two channels. Each channel contains 54 holes equally spaced apart at 3.622 centimeter intervals. The lower one also has 53 extra holes for use as part of the eliminator strips support mechanism.

The waveguides are bolted to the upper and lower mounting channels using the waveguide top and bottom supports as shown in Figure 47. The waveguides are 2.54 by 5.08 centimeter aluminum square tubes with a 1.854 millimeter wall thickness. The design dictates that to achieve the proper radiation pattern the waveguides must show a 1.082 centimeter spacing.

When the waveguide assemblies are attached to the mounting channels on the antenna support frame, the monitor waveguide can be fitted to slots in the backside of the waveguides and used as a vertical alignment tool. Bolts through the top and bottom waveguide supports are then tightened in place.

The floating mount connectors on the coaxial cable assembly are next secured to a plate referred to as a connector mounting bracket, bolted to the top of the support frame. The floating mount connector is very important to the design as it allows for misalignment due to manufacturing tolerances in 2 planes and thus permits use of a plug in phase shifter. Figure 48 shows the connector mounting bracket assembly.

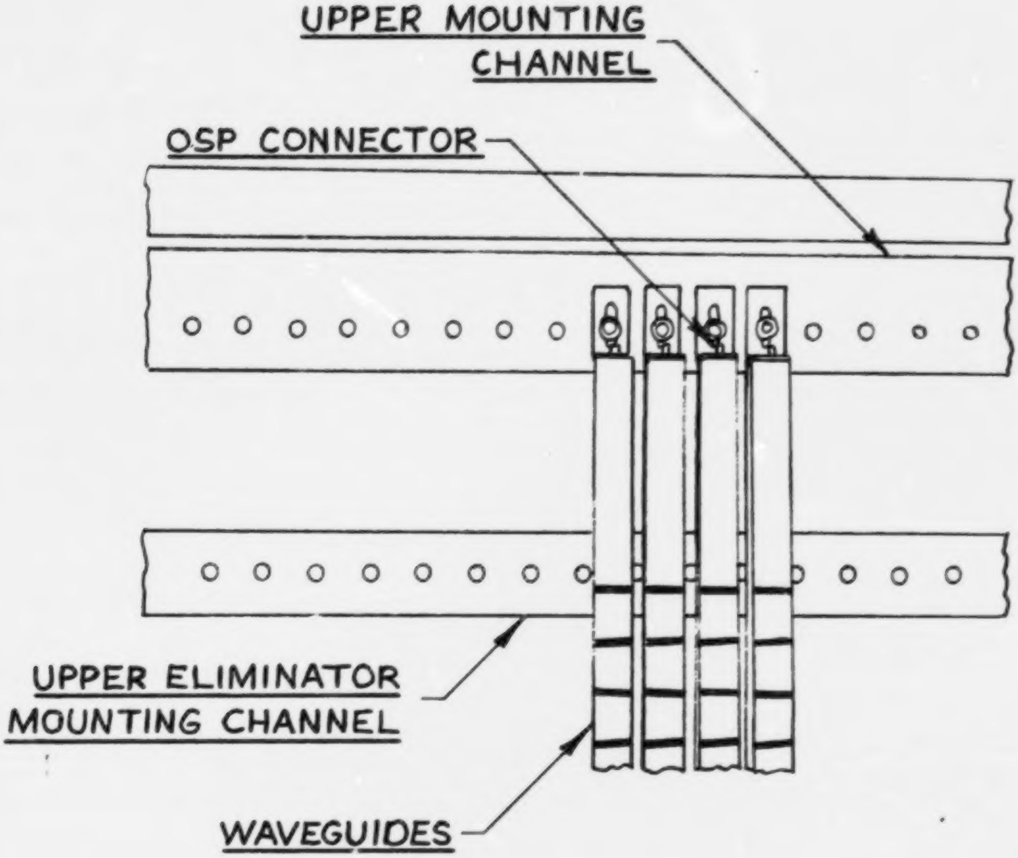

UPPER MOUNTING CHANNEL
OSP CONNECTOR
UPPER ELIMINATOR MOUNTING CHANNEL
WAVEGUIDES

Figure 47 Waveguide Mounting

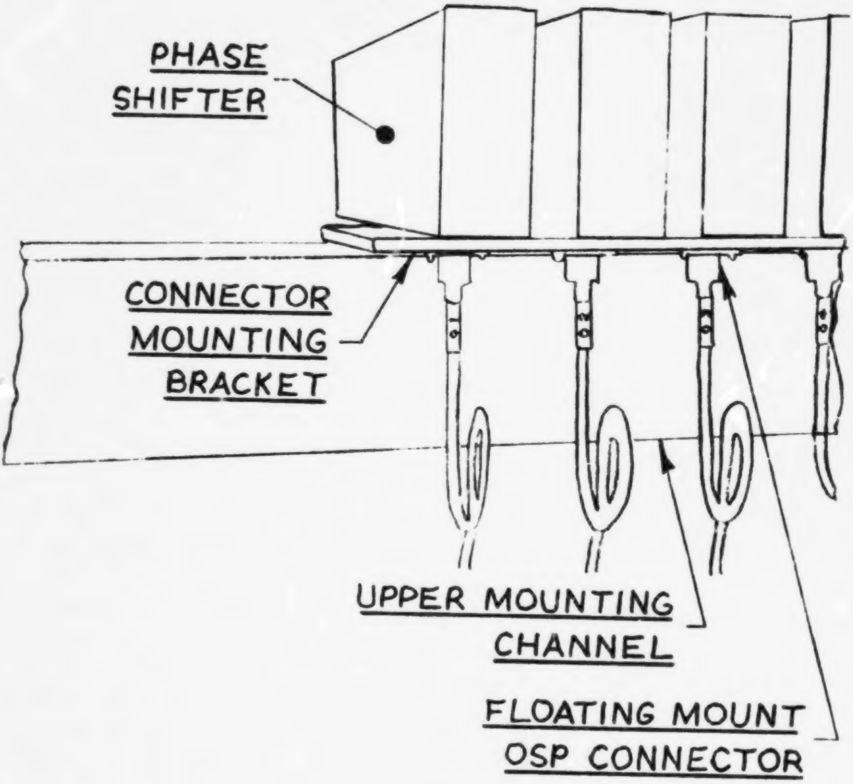

PHASE SHIFTER
CONNECTOR MOUNTING BRACKET
UPPER MOUNTING CHANNEL
FLOATING MOUNT OSP CONNECTOR

Figure 48 Phase Shifter Mounting

As a backplane to the radiating elements, eliminator strips are bolted in between each waveguide. They mount to the eliminator mounting channels and the bottom mounting channel. Spacers are placed between the channel and the strip to situate the eliminator a quarter wavelength behind the front face of the waveguide. This is a short circuit at microwave frequencies.

Figure 49 shows the entire waveguide assembly just described mounted to the antenna support.

4.4 Corporate Feed Mounting

The corporate feed is located on the upper back of the antenna frame as shown in Figure 50. It has 54 OSP connectors located on its top edge which are the feed outputs. On the bottom edge, one SMA connector uses a semi-rigid cable to interface to the microwave source.

The corporate feed is mounted to the antenna support frame with four bolts. It is situated in this position to enable direct non-cable connection to the phase shifters. The feed output connectors are located in the same horizontal plane as those on the connector mounting bracket. The approximate weight of the corporate feed is 90 kilograms.

4.5 Phase Shifter Mounting

As shown in Figures 48-50, the phase shifters are mounted to the top of the connector mounting bracket and corporate feed. Since the connectors on these two components are in

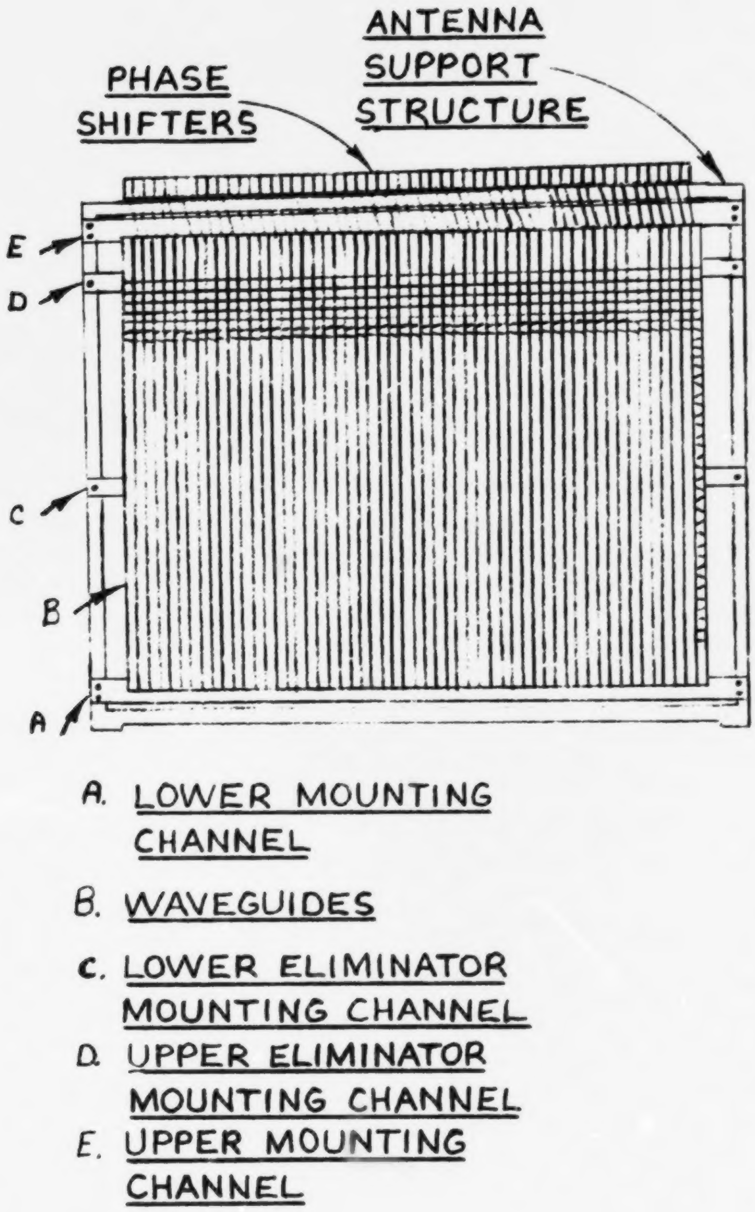

ANTENNA SUPPORT STRUCTURE
PHASE SHIFTERS
E
D
C
B
A
A. LOWER MOUNTING CHANNEL
B. WAVEGUIDES
C. LOWER ELIMINATOR MOUNTING CHANNEL
D. UPPER ELIMINATOR MOUNTING CHANNEL
E. UPPER MOUNTING CHANNEL

Figure 49 Waveguide Assembly

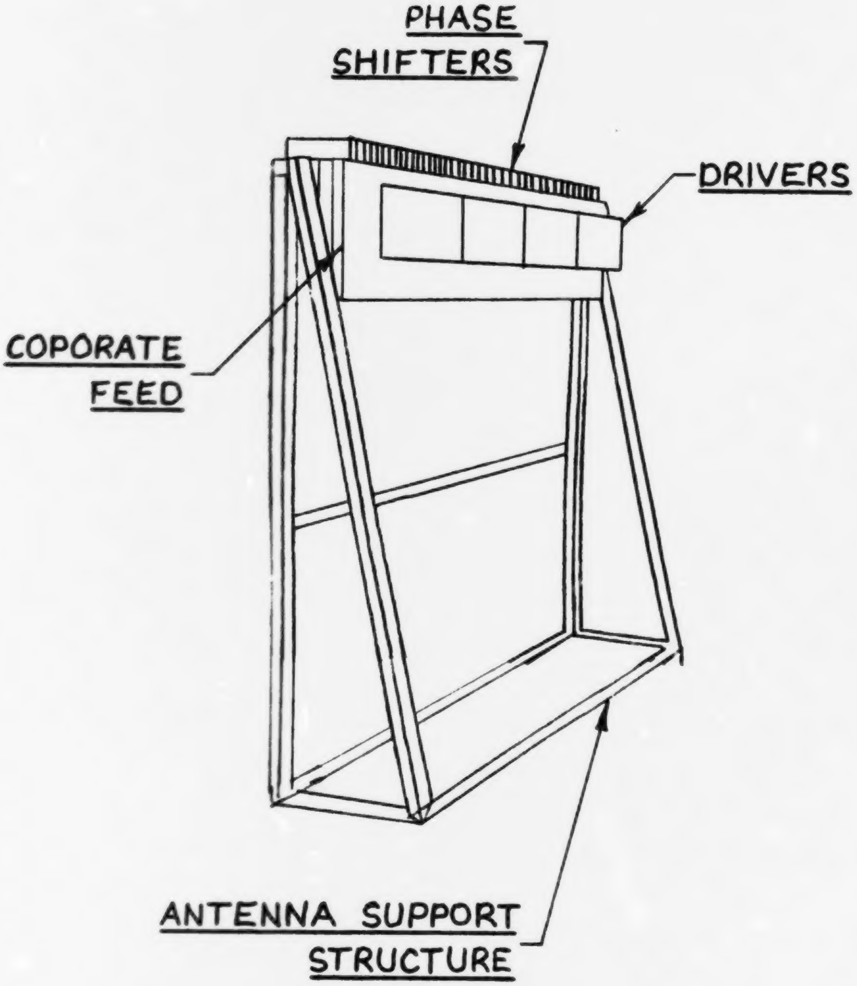

PHASE SHIFTERS
DRIVERS
COPORATE FEED
ANTENNA SUPPORT STRUCTURE

Figure 50 Corporate Feed and Electronic Driver Location

the same horizontal plane, the phase shifter simply plugs into place. The two ouputs on the shifter are spaced 170.28 mm apart which is exactly the same distance between connectors on the feed,and mounting bracket.

A 10 pin ribbon cable connector located on the top of each phase shifter mates with its corresponding cable from the Beam Steering Logic Unit or BSLU electronics. This cable carries the driver signals which switch the four bits of the phase shifter on and off.

To secure the phase shifters, eight centimeter long, small diameter screws are mounted in a right angle bar on the antenna support frame, projecting upward between each second shifter. By using a wingnut, a steel washer, and a rubber washer (for isolation), the phase shifters are retained in a stationary position. The approximate weight of each phase shifter is a kilogram.

4.6 Control Electronics Mounting

The control electronics can be divided into BSLU driver assemblies and other electronics. These driver circuits are distributed on four wire wrapped boards of 14 driver circuits each for a total of 56. Each phase shifter has a corresponding driver circuit and connecting cable. The boards are bolted to the feed with output connectors facing upward towards the phase shifters as shown in Figure 50. All other electronics are housed in a standard "Eurocard" card rack attached to a separate support frame bolted to the pedestal.

4.7 Monitor Assembly

The monitor waveguide accepts an input from each of the vertical antennas for use in fault determination and analysis. It is made of the same square aluminium waveguide as the phased array with slots machined to couple a small amount of energy from the array. Each of these slots is physically matched to a larger 2.54 by 2.54 centimeter **opening** in the backside of all of the phased array waveguides. The actual location of this connection is as shown in Figure 51, near the bottom of the array. The monitor narrow wall dimension is almost identical to the opening in the array elements fitting directly into each waveguide to a depth equal to the waveguide wall thickness.

On each end of the monitor waveguide output flanges (Figure 52) are attached. For measuring purposes one output will be loaded and the other connected to test equipment through a waveguide to coaxial adapter.

As described above the monitor fits into openings on the waveguides. To provide secure mounting, a specific clamping procedure is used. It uses clamp bars on the front of the radiators and a clamp bracket on the back of the monitor. Two 100 mm screws with the appropriate hardware hold the monitor against the array with a vising action.

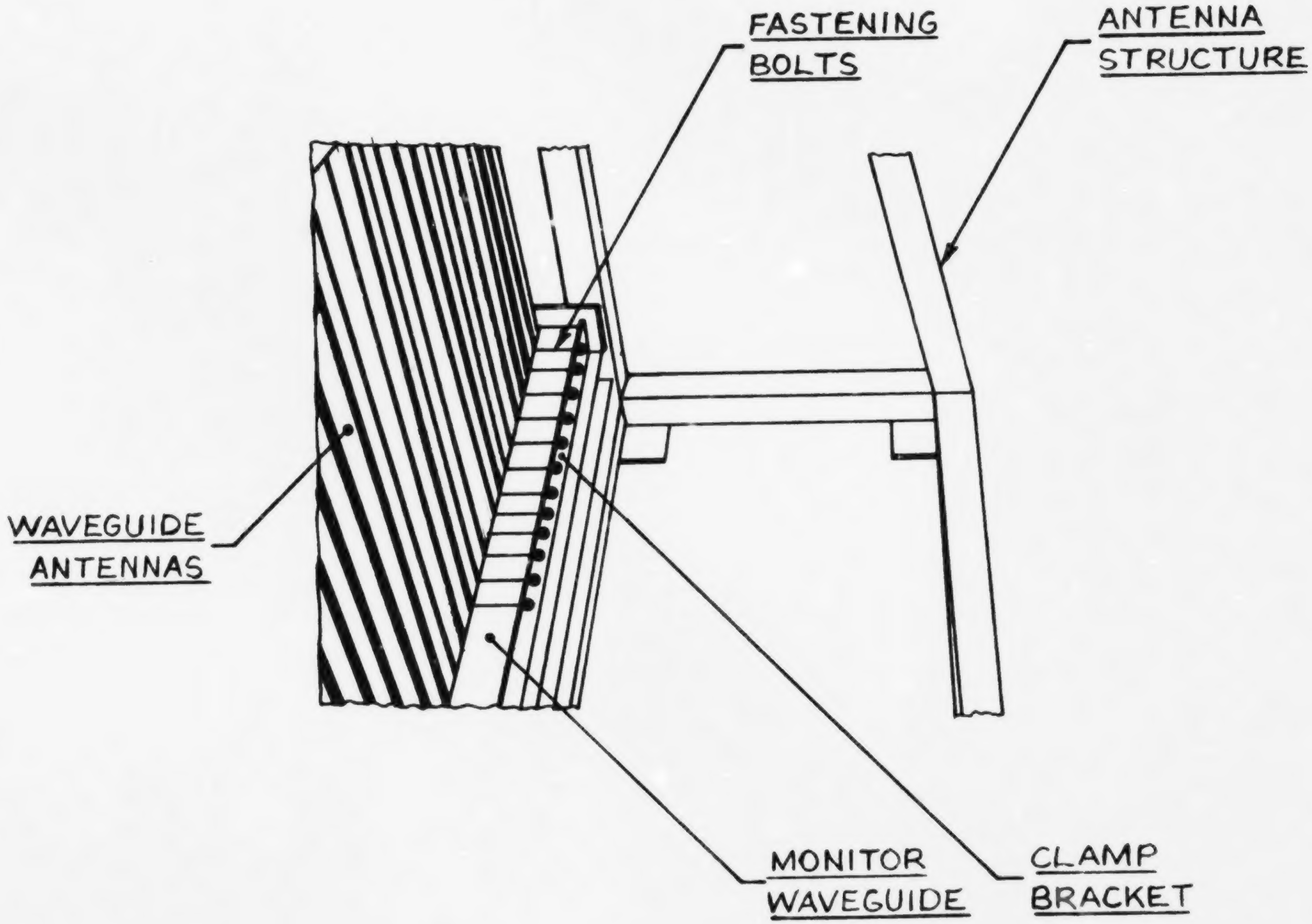

FASTENING BOLTS
ANTENNA STRUCTURE
WAVEGUIDE ANTENNAS
MONITOR WAVEGUIDE
CLAMP BRACKET

Figure 51 Monitor Waveguide Assembly Location

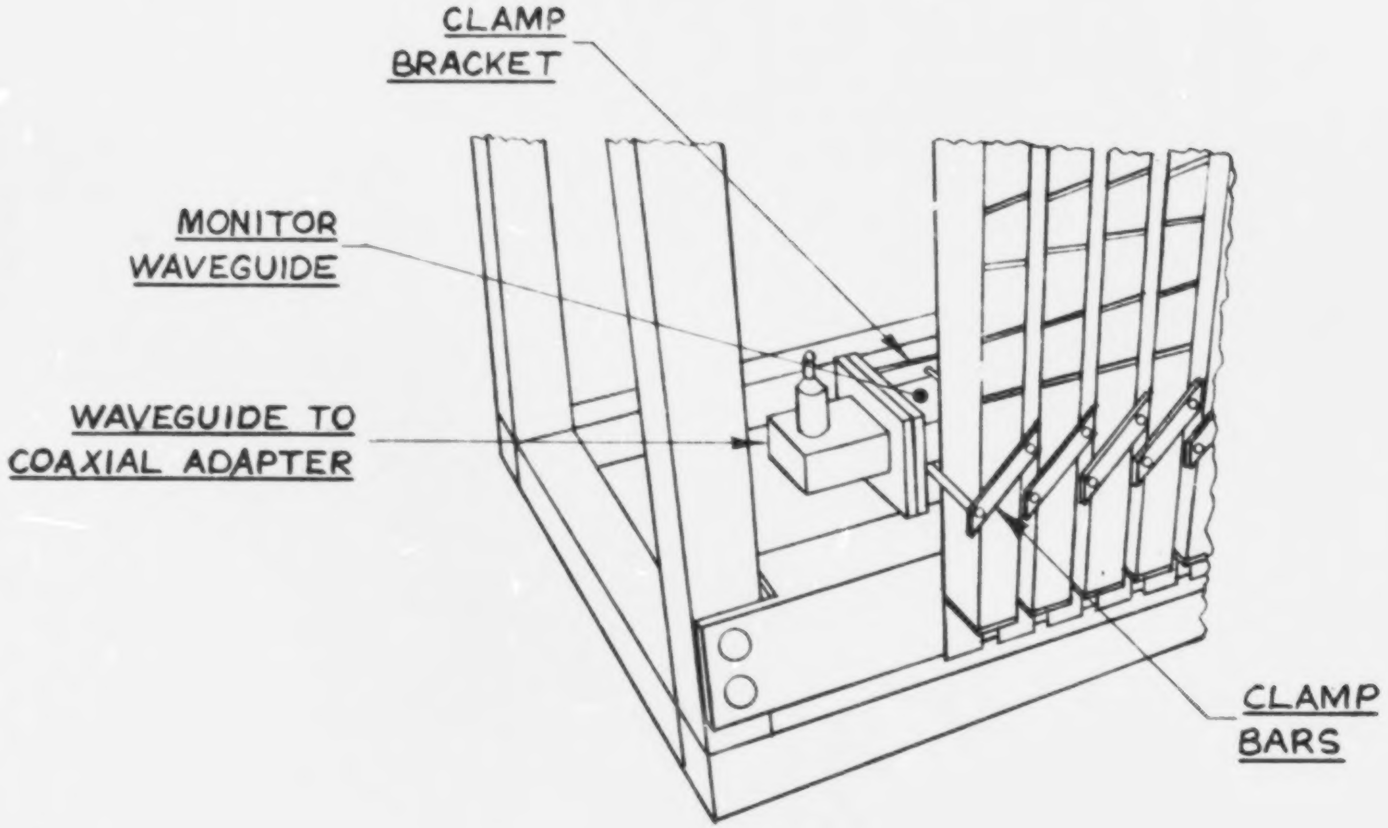

CLAMP
BRACKET
MONITOR
WAVEGUIDE
WAVEGUIDE TO
COAXIAL ADAPTER
CLAMP
BARS

Figure 52 Monitor Connector Location

4.8 Microwave Source Mounting

The microwave source which powers the waveguide radiators is located on the rear of the antenna support below the corporate feed. All the components previously described as part of the source such as the amplifier, excitor, etc., are mounted on a 610 by 610 mm aluminium plate. This plate is bolted to the antenna support, with seven bolts, directly below the feed on the rear left hand side.

Interconnection to the control electronics is provided using discrete wiring on two D-type connectors. RF energy is fed to the corporate feed from the microwave source using a semi-rigid cable with SMA connectors. A similar cable provides RF energy to the I.D. antenna located external to the housing. The location of the microwave source was selected to minimize the cable run length to the I.D. antenna. The approximate weight of the microwave source mounted on the aluminimium plate is about six kilograms.

4.9 Enclosure and Pedestal

The enclosure provides environmental protection for the antenna and control electronics. It was designed as a housing surrounding the antenna and electronics and mounted to a pedestal. The pedestal is a rigid support structure which elevates the antenna above the ground so that the lowest radiating slot in the array is at least 1 meter above the ground.

The housing frame is made up of right angle aluminium stock cut to size and welded together. It is constructed in a rectangular shape 2.08 meters high, 2.49 meters wide, and .97 meters deep. Additional material is welded inside the front face of the frame to provide a radome support. Aluminium sheets 1.016 millimeters thick are riveted onto the frame to provide walls which can be insulated with various materials. On the rear of the housing, hinges and a handle are used as part of a dual section door which opens outward from the middle. These doors provide access for service personnel performing maintenance or repair functions.

Adjustments of azimuth and elevation angles are required during installation of MLS systems. Azimuth angle must be set to within two degrees before final alignment can be performed with electronic boresighting using the control electronics. Physical azimuth alignment is achieved by positioning the slotted mounting feet about the bolts protruding from the concrete foundation. Elevation adjustment is accomplished be shimming the appropriate mounting feet.

Besides using lightweight aluminium construction, another concession to fragibility is achieved. Shear pins were used to tie the pedestal to the concrete foundation embedded in the ground. If a collision with the unit occurs, these pins will shear reducing damage to the aircraft or ground equipment. During installation or shipping two methods are available for moving. Forklift slots have been built into the pedestal and lifting eye hardware is provided on the top of the enclosure for handling by crane.

The system currently in operation at Sydney airport is using the discussed pedestal but is enclosed in a larger wooden building to provide greater freedom of access and shelter for technical staff working on the system.

During the development of the MLS azimuth antenna system, the mechanical design was given a low priority compared to the electrical performance of the system. This prototype system will be used as a baseline design and updated and improved prior to production.

5. GROUND INSPECTION TESTS

5.1 General

Following testing of the phased array antenna at David Florida Labs it was crated and shipped by truck to Micronav's facility in Sydney, Nova Scotia. The antenna was integrated with electronics assemblies, a microwave source, power supplies and an I.D. antenna to become an operational MLS azimuth transmitter system. No major difficulties were encountered during the integration process and the completed assembly was then housed in a specially designed building.

The azimuth transmitter was tested initially at Micronav's facility in Point Edward. The site was surveyed to provide survey points at 1 degree radials plus and minus 45 degrees of a centerline relative to the antenna location. Operation was confirmed with ground testing using a van equipped with an aircraft model Bendix MLS 20A receiver. The receiver operated correctly throughout the $\pm 40^\circ$ required coverage area and system parameters of sidelobe levels, beamwidth, and beam shape were measured and found to meet or exceed our specifications.

The azimuth antenna was subsequently moved to the Sydney Airport and installed near the threshold of runway 14. Ground testing was repeated for this new location and the test procedures, tolerance limits, and measured results contained in Appendix 9.

5.2 Overview

The Micronav Limited prototype azimuth only Microwave Landing System (MLS) provides proportional guidance to $\pm 40^{\circ}$ and is presently situated 125 feet from the threshold of runway 14 on centerline at Sydney Airport.

Ground testing has been conducted to determine correct system operation to ICAO Annex 10 requirements for signals in space. For all measurements the site was powered with a portable generator and a Bendix MLS 20A aircraft receiver was used to monitor signals. The receiver was mounted in a van equipped with a directional horn pointed toward the MLS site.

Accurate positioning information for the ground tests was provided by one degree radial survey marks on the intersecting runway relative to the MLS site.

Extensive ground testing revealed that the Micronav MLS azimuth system met or exceeded the requirements of ICAO Annex 10 and Standards and Recommended Practices, for signals in space.

5.3 Test Summary

Ground testing provided valuable data on a number of important system parameters. The tests evaluated the RF signal accuracy and stability and well the internal tuning of transmissions and their sequence. Sidelobe measurements were made with the system scanning by observing the logrithmic video output of the MLS receiver for locations throughout the $\pm 40^{\circ}$ coverage area. The transmissions from the I.D. antenna were measured and verified against the ICAO standards. A summary sheet of ground inspection tests is included as Table 12.

Table 12 SUMMARY SHEET OF GROUND INSPECTION TESTS

TEST REFERENCE	FUNCTIONAL DESCRIPTION	I.C.A.O ANNEX 10 REFERENCE
G - 1	Station RF Frequency Accuracy	3.11.4.1.3
G - 2	Station Rf Frequency Jitter	3.11.4.1.3
G - 3	D.P.S.K. Phase Shift	3.11.4.4.3.1
G - 4	Scanning Beamwidth and Shape	3.11.5.2.1
G - 5	Dynamic Sidelobes	G.M. Section
G - 6	Function Timing (Sequence)	3.11.4.3.4
G - 7	Function Timing (Internal)	3.11.4.3.5
G - 8	Function Rates	3.11.4.3.3
G - 9	Function Preambles	3.11.4.4
G - 10	Basic Data Coding	3.11.4.8.2
G - 11	Facility Identification (MORSE)	3.11.4.6.2.1
G - 12	Interference	3.11.4.1.4

6. FLIGHT INSPECTION TESTS

6.1 General

Micronav has performed flight checks of its azimuth MLS transmitter using a leased twin engine Navahoe aircraft. The aircraft was outfitted with the Bendix MLS 20A receiver previously used for ground testing. An omni-directional stub antenna was mounted on the skin of aircraft above the cockpit near the centerline of the aircraft. This antenna was used to provide signal for the MLS receiver.

Using the local DME to provide distance information the effective area of proportional guidance coverage was determined. Guidance information was consistently received at distances in excess of 50 nautical miles from the transmitter; without flags or alarms indicating unusable signals. The coverage area of ± 40° of centerline was also confirmed by flight checks.

Simulated approaches on runway centerline indicated a stable, sensitive system with which the pilot found no apparent annomolies. Micronav did not have the sophisticated testing equipment such as tracking theodolites required to determine more specific performance results for the system. Ministry of Transport however agreed to evaluate the system using the attached MLS Flight Test Plan.

6.2 Objective

The prime objective of the MLS Flight Test Plan is to evaluate Micronav's Azimuth MLS prototype and determine if it meets or exceeds ICAO ANNEX 10 requirements for radiated signals. It is understood that Transport Canada is still in the process of establishing a flight test capability for evaluation of MLS to ICAO standards and their flights testing of the system is much appreciated.

The flight test program should determine if the ground station radiated signals are meeting ICAO format and are providing sufficient coverage and accuracy. The flight tests will determine alignment of the system relative to the runway centerline. Following this, course structure accuracy and coverage limits will be defined. As well, guidance parameter checks and a simulated approach should verify system operation.

For all flight testing the receiver flag, Raw Cross Pointer, Corrected Cross Pointer, Theodolite and DME data should be recorded. During all tests the azimuth station will be configured for a 2400 meter runway length. Positioning information for tests is to be provided by tracking theodolite and airport TACAN/DME. A flight test summary is included as Table 13 and a complete flight test plan is attached as Appendix 10.

Table 13 FLIGHT TEST SUMMARY

Run Number	Run Type	AZIMUTH ANGLE	ALTITUDE	SITE DISTANCE
1	Level Crossover	0 Deg.	760m AGL	22km
2	" "	+ 38 "	"	"
3	" "	+ 30 "	"	"
4	" "	+ 20 "	"	"
5	" "	+ 10 "	"	"
6	" "	+ 2 "	"	"
7	" "	0 "	"	"
8	" "	- 2 "	"	"
9	" "	- 10 "	"	"
10	" "	- 20 "	"	"
11	" "	- 30 "	"	"
12	" "	- 38 "	"	"
13	" "	0 "	" AGL	73km
14	Coverage Arc	-50° to $+50^{\circ}$	" AGL	45km
15	Coverage Arc	-50° to $+50^{\circ}$	460m AGL	9km
16	Stimulated APP	0°	3° EL	22km

AGL - above ground level

6.3 Results

Micronav's flight tests conducted by company personnel found no indication that the system did not meet ICAO ANNEX 10 criteria for radiated signals.

Minstry of Transport flight testing was not completed due to aircraft equipment difficulties however a portion of the flight checks were flown and MOT repeated Micronav's ground testing. Flight tests should be completed within the month and a copy of the data will be provided to Micronav.

MOT conducted azimuth aligment runs, azimuth coverage probes, and an azimuth coverage arc during flight testing at Sydney Airport. They did not find any problems during these flights and stated:

> "Recognizing that the unit is a prototype, only the guidance characteristics of the signal in space were assessed. The initial implications are that, from this point of view, the system will meet all ICAO tolerances."

7. EXPERIMENTAL PROCEDURES AND RESULTS OF TOTAL PHASED ARRAY ANTENNA

7.1 Experimental Procedures

Antenna testing was conducted on the Communication Research Center David Florida Laboratory (DFL) test range near Ottawa. The phased array antenna under test consisted of 54 slotted waveguide radiators, 54 four bit phase shifters, and a corporate feed network. The phase shifters were attached to driver and control electronics located on the back side of the antenna assembly. Each phase shifter had individual drivers controlled by a software sequence stored in a PROM.

In normal MLS operation the PROM sequence would steer the beam TO-FRO over ± 42° relative to boresight. Specially constructed control electronics caused the beam to scan to a preselected angle and remain at that angle. A four digit hexadecimal thumbwheel switch was used to select any desired pointing angle for the main beam. The switch setting selects a particular phase distribution across the face of the array.

The phased array antenna was mounted on a pedestal in the anechoic chamber at DFL. The pedestal position was electronically controlled so that the antenna could be mechanically scanned 360° in azimuth and ± 45° in elevation. The phased array was used as a receiving antenna for an RF radiation source mounted about 46meters above ground level about 365meters away on a supporting tower. The output of the corporate feed was fed to the antenna range Scientific Atlanta test system.

All components in the phased array are reciprocal devices.

The pointing angle of the main beam of the phased array is produced as a result of a particular phase distribution across the array. The phase distribution is determined by the state of each of the 54 phase shifters. Appendix 1 is a table of switch settings and phase shifter states for discrete beam pointing angles plus an alternate set of phase distribuitions or scan sequences which will point the beam in the same manner but may provide lower sidelobe levels.

Antenna range testing is required to determine the following factors:

1. scan coverage and beam pointing accuracy
2. effective sidelobe levels throughout the coverage area
3. beam width and beam shape
4. grating lobe locations & magnitude
5. elevation patterns
6. azimuth radiation pattern for operational frequency extremes of 5030, 5090 and mid band 5060 MHz
7. elevation patterns over the frequency band
8. phase shifter effect on pattern ($22.5^{\circ}/ 45^{\circ}/ 90^{\circ}/ 180^{\circ}$) on boresight
9. effect of phase shifter failure on sidelobe & beamwidth

7.2 Results

Azimuth 1 Degree Increment Patterns

Appendix 2 contains azimuth radiation patterns with the beam pointed at each 1° increment from -42° to 42°. In all cases the elevation angle is aligned to the peak of the elevation pattern, about 2.5 degrees. All patterns are taken at a frequency of 5060 MHz.

These patterns provide the following information:

1. The 3 db beamwidth on boresight is 2.0 degrees for the main beam.
2. The main beam can be scanned $\pm 42^\circ$ from boresight.
3. The beam can accurately be pointed to any location throughout the $\pm 42^\circ$ sector to the measuring accuracy of the test equipment. This validates the beam scanning algorithms.
4. Sidelobes greater than $\pm 5^\circ$ from the main beam inside the $\pm 42^\circ$ coverage area typically do not exceed -20dB relative to the main beam.
5. Near in sidelobes are typically -17db or less relative to the main beam.
6. Sidelobe structure changes as the beam position is changed.

7.3 Azimuth Phase Offset Patterns

Appendix 3 contains azimuth radiation patterns with the beam pointed at 0°, boresight, for 22.5°, 45°, 90° and 180° phase offsets. These patterns are recorded for frequencies 5030, 5060 and 5090 MHz. A phase offset is a state where all phase shifters are set to an identical phase delay other than zero. For example a phase offset of 180° would set all 54 phase shifters in the array to 180° of phase delay. Since this does not change the phase gradient across the array, the beam remains pointed at zero degrees.

Phase offset azimuth patterns provide a useful indication of phase shifter effects without introducing phase quantization errors.

These patterns provide the following information:

1. The phase shifters do not significantly alter the effective beam peak amplitude. In all cases the variation is less than 0.4 dB.

2. No appreciable change in sidelobes or main beam shape was recognizable for any phase offset at 5030, 5060 or 5090 MHz.

7.4 Elevation Patterns at 5030, 5060, 5090 MHz.

Appendix 4 contains elevation radiation patterns with the beam pointed at 0°, boresight, for frequencies 5030, 5060 and 5090. The antenna is also mechanically aligned to boresight in the azimuth plane.

These patterns provide the following information:

1. Roll off at zero degrees of elevation in dB per degree.
2. At 15° elevation angle the signal is 12 dB down from beam peak.
3. No significant differences in the pattern are observed over the operational frequency band of 5030 to 5090 MHz.

NOTE: The antenna was not mechanically aligned to 0° in elevation and 0° on the antenna pattern plots is only a reference point to the beam peak.

7.5 Azimuth Patterns for 1° Elevation Increments

Appendix 5 contains azimuth radiation patterns with the main beam pointed at 0°, boresight, in azimuth angle while the elevation angle is incremented in 1° steps. Azimuth radiation patterns are recorded for elevation angles from -5° to $+15^\circ$.

These patterns provide the following information:

1. Azimuth main beam beamwidth and beamshape remains within acceptable units throughout the useful elevation angles.
2. No appreciable increase in sidelobe level is observed at any elevation angle selected.

7.6 Grating Lobes

Appendix 6 contains azimuth radiation patterns with the main beam pointed at 40° and 45° of azimuth angle while recording a larger azimuth scan of ± 90 degrees of azimuth angle.

These patterns provide the following information:

1. A main beam pointing angle of 45° creates a grating lobe at -67° and -6 dB relative to the main beam.
2. A main beam pointing angle of $+40^\circ$ creates a grating lobe at -77° and -14 dB relative to the main beam.

7.7 Phase Shifter Failure Test Patterns

Appendix 7 records azimuth radiation patterns with an azimuth pointing angle of 0°. Plots were taken with the center phase shifter disconnected, a single phase shifter removed on one side of the array, and two phase shifters disconnected. These measurements were repeated with selected phase offsets.

1. Single phase shifter failures and two phase shifter failures create worst case sidelobes well below the required ICAO sidelobe requirements.
2. The patterns indicate that up to four of five randomly spaced phase shifter failures may be tolerable but this well require actual field testing and flight testing to confirm.

8. DISCUSSION OF SYSTEM RESULTS

The MLS azimuth antenna performed reasonally well in all areas. The major deviation from predicted performance was the increased sidelobe level. The beamwidth and beamshape of the radiation patterns were measured and found correct. Pointing accuracy in azimuth angle was as accurate as could be measured.

Individual system components could be improved in a variety of ways to yield better results. This would typically allow for a relaxation of production tolerance and reduce trimming and adjustment procedures providing a lower cost final product.

Waveguide Assemblies

1. Waveguide length can easily be decreased to reduce the height of the phased array antenna.
2. Alignment of waveguides on the antenna frame presently varies ± 0.76 mm. corresponding to a phase variation of ± 4.5 degrees. Provision of an extra waveguide support should allow the front face of the antenna to be aligned within ± 0.25 mm.

Phase Shifters

1. Size of the phase shifter should be reduced to lower fabrication cost, reduce absolute attenuation,and decrease delta insertion loss between bits.
2. Better source control of diodes and better diode placement techniques would reduce trimming.
3. Wet etch techniques should be investigated to replace sputtering for reduced cost.
4. Connectors must be assembled in a manner to avoid overstressing the connector-microstrip solder interface when clamped in position.

Corporate Feed

1. Weight should be reduced by redesign of a new corporate feed box of thinner materials or if required honeycomb structures.
2. Reduction of the microstrip substrate thickness to 20 mil from 62 MIL would reduce the size.
3. Phase trimming stubs should be modified to have less effect on the circuit; most likely by reducing their width.
4. Additional iterations of the corporate feed network should be fabricated to better define the theory related to high division ratio Wilkinson type power dividers. This should also allow power division ratios to be redefined so that amplitude trimming is not required.

9. CONCLUSION

An MLS azimuth antenna system has been designed, built and sucessfully demonstrated to meet or exceed ICAO Annex 10 standards. The system is operational and has provided excellent results during ground and flight testing relative to existing MLS designs. Detailed analysis of overall antenna performance relative modification of design parameters were required to achieve a realistic final design.

Future MLS azimuth antenna work is required to "production design" the various components of the system. Improvements in the areas of weight reduction, size reduction and sidelobe level supression are desireable however they will have minimal effect on system performance from a user's vantage point.

APPENDIX 1

SCAN PROGRAM 1

for

selecting beam pointing angle

```
CORRECTED BEAM ANGLES FOR SCAN PROGRAM 1
DATE: 07/01/84
FREQUENCY= 5030 MHZ

                                                                                   PAGE 1
 THUMBWHEEL        CRCTD                        PHASE SHIFTER STATES
 SWITCH            BEAM                 LEFT                                 RIGHT
SETTING            POS.     2222222221111111111                     1111111111222222
                            765432109876543210987654321 0123456789012345678901234560

  0  0  0  0    46.04604    D6F81A3C5E7092B4D6F81A3C5E7 092B4D6F81A3C5E7092B4D6F81A
  0  0  0  1    46.01866    D6F81A3C5E7092B3D6F81A3C5E7 092B4D6F81A3D5E7092B4D6F81A
  0  0  0  2    45.99416    D6F81A3C5E7092B3D5F81A3C5E7 092B4D6F81B3D5E7092B4D6F81A
  0  0  0  3    45.96536    D6F81A3C5E7092A3D5F81A3C5E7 092B4D6F81B3D6E7092B4D6F81A
  0  0  2 15    44.99568    A3C6E81A3C5E7092B4E7092B4E7 092C5E7092C5E7092B4D6F82A4D
  0  0  5 13    44.00209    7092C5E71A3C5F81A3C6F81B4D7 093C5F81A4D6F81B4D6F92B4E70
  0  0  5 14    43.97839    7092C5E70A3C5F81A3C6F81B4D7 093C5F81A4D6F81B4D6092B4E70
  0  0  8 12    42.99373    3C6F92C5E81A4D6F92B5E71A4D7 093C6F92B5E71A3C6F82B4E71A4
  0  0 11 11    41.98599    093C6092C5F82B4E71A4D70A3D7 093D6093C6F92C5E81B4E70A4D7
  0  0 14 11    41.00661    C6F93D70A3D6093C6F93C6093D6 0A3D70A4D71A4D70A3D6093D71A
  0  0 14 12    40.98663    C6F93D60A3D6093C6F93C6093D6 0A3D70A4D71A4D70A3D60A3D71A
  0  1  1 12    40.00425    92C60A4D71B4E81B4E82B5F93C6 0A4D71B5E82C5F82C5F93C60A4E
  0  1  1 13    39.97931    92C60A4D71A4E81B4E82B5F93C6 0A4D71B5E82C5F82C6F93C60A4E
  0  1  4 14    38.99923    5F93D71B5E82C6F93D71B4E82C6 0A4E82C5F93D71A4E82B5F93D71
  1  0  0  0    38.10141    2C60A4E82C60A4E82C60A4E82C6 0A4E82C60A4E82C60A4E82C60A4
  1  0  0  5    37.98831    2C60A4E82C60A4D71B6FA4E82C6 0A4E82C61A5F93C60A4E82C60A4
  1  0  3  8    37.00503    E92D71B5FA4E82C60A4E93D71C6 0A4F93D72C60A4E82C61B5F93E7
  1  0  3  9    36.98245    E92D71B5F94E82C60A4E93D71C6 0A4F93D72C60A4E82C71B5F93E7
  1  0  6 12    35.99099    B5F93E92D71C60A4F93D82C71B6 0A5F94E83D71C60A4F93E72D71B
  1  0  9 15    35.00349    71C60B60A5F94E83D72C71C61B6 0A5FA4F94E93D82C71B60A50A4F
  1  0 10  0    34.98756    71B60B60A5F94E83D72C71C61B6 0A5FA4F94E93D82C71B60A50A5F
  1  0 13  6    33.98940    3D83D83D82D72C61B61B60B50B5 0B50B50A5FA5FA4E93E83D83D83
  1  1  0 11    33.00576    FA4FA50A50A50A5FA5FA5FA50A5 0B60B61B61B61B60B60B60B61C6
  1  1  0 12    32.98297    FA4FA50A50A50A4FA5FA5FA50A5 0B60B61B61B61C60B60B60B61C6
  1  1  4  1    32.00637    B61C72D72D83D83E83E94F94FA5 0B61C71C72D82D83D83E93E94FA
  1  1  4  2    31.98977    B60C72D72D83D83E83E94F94FA5 0B61C71C72D82D83D83E93E940A
  1  1  7  7    30.99647    72D93FA4FA50B61C72D83E94FA5 0B61C72D83E94FA50B61C61D73E
  2  0  0  0    30.94485    72D83E94FA50B61C72D83E94FA5 0B61C72D83E94FA50B61C72D83E
  2  0  3  4    30.00146    4F950B71D83E94FA50B72D83EA5 0B62D83E950B61C72D83F950B71
  2  0  3  5    29.98063    4F950B71C83E94FA50B72D83EA5 0B62D83E950B61C72D84F950B71
  2  0  6 12    29.00038    0B61C84EA50C72D84FA51C73E95 0B72D94FB61C83E940B62C84FA5
  2  0  6 13    28.97744    0B61C84EA50B72D84FA51C73E95 0B72D94FB61C83E950B62C84FA5
  2  0 10  5    27.99417    B72E950C72E950B62D940B72D95 0B73E950C73EA50B72E940B72E9
  2  0 13 14    26.99188    83EA62D840B72E950C73FA61D94 0C73FA61D940B72E950C83EA62D
  2  1  1  7    26.00668    3FB72EA51D940C73FA62E951D84 0C83FB72EA61D940C73FB62E951
  2  1  1  8    25.98989    3FB62EA51D940C73FA62E951D84 0C83FB72EA61D940C73FB62EA51
  2  1  5  2    24.99593    FB63FB72EA62EA51D951C840C84 0C840C84FB73FB62EA62E951DA5
  3  0  0  0    24.29094    C840C840C840C840C840C840C84 0C840C840C840C840C840C840C8
  3  0  1  1    23.99480    B73FB84FB74FC83FB73FB740C84 0C840C951D951D841C951C851D9
  3  0  4 12    23.00177    73FC740C851D951DA62EA73FB74 0C951D962EA63FB73FB840C941D
  3  0  4 13    22.98870    73FC740C851D951DA62EA63FB74 0C951DA62EA63FB73FB840C941D
  3  0  8  7    21.99307    3FB841D952EA73FB840D962EB74 0C952EA730C851D962EB73FC851
  3  0 12  3    21.00873    EB740DA62FB841DA63FC851EA73 0D962FB841DA63FC851EA630C95
  3  0 12  4    20.98828    EB740DA62FB841D963FC851EA73 0D962FB841DA73FC851EA630C95
  3  0 15 15    20.00329    A630DA63FC952FB841EA740DA73 0D9630C962FC851EB741DA630DA
  3  1  0  0    19.98724    A630CA63FC952FB841EA740DA73 0D9630C962FC851EB741DA640DA
  3  1  3 12    19.00254    62FC9630C9630C963FC9630C963 0DA740DA741DA740DA740DA741E
  3  1  3 13    18.99403    52FC9630C9630C963FC9630C963 0DA740DA741DA740DA740DA741E
  3  1  7  8    18.00225    1EB8530C9630DA741EB852FC963 0DA741EB852FC9630DA740DB852
  3  1  7  9    17.98533    1EB853FC9630DA741EB852FC963 0DA741EB852FC9630DA741DB852
  4  0  0  0    17.97052    1EB852FC9630DA741EB852FC963 0DA741EB852FC9630DA741EB852
  4  0  3 11    17.00562    DA752FC9630EB852FC9641EB863 0DA852FCA741EB8520DA741EB96
  4  0  3 12    16.99094    DA742FC9630EB852FC9641EB863 0DA852FCA741EB8520DA741EC96
```

```
                                                                                         PAGE 2
 THUMBWHEEL       CRCTD                           PHASE SHIFTER STATES
 SWITCH           BEAM                  LEFT                                    RIGHT
SETTING           POS.     222222221111111111                              11111111112222222
                           765432109876543210987654321 01234567890123456789 0123456

 4  0  7  9     15.99527   9631EC9630EB8620DA8520DA853 0DB8630EB8630EA8520DA742FDA
 4  0 11  7     14.99818   41FDA8530EB9630EB9641FCA753 0DB9641FCA7520DA7520DB8631F
 4  0 15  5     14.00588   0DB9642FDB8641ECA7520EB9752 0EB97520EB9642FCA8531ECA753
 4  0 15  6     13.98516   0DB9642FDB8631ECA7520EB9752 0EB97520EB9642FDA8531ECA753
 4  1  3  5     12.99134   B96521ECA8531FCA8631FDB8642 0ECA8531FDA8641FDB8642FEBA7
 4  1  7  1     12.00224   7531FDB97420ECA86420ECA8642 0ECA86420ECA86420EC97531FDB
 4  1  7  2     11.98373   7531FDB96420ECA86420ECA8642 0ECA86420ECA86420ECA7531FDB
 5  0  0  0     11.86961   6420ECA86420ECA86420ECA8642 0ECA86420ECA86420ECA86420EC
 5  0  3  6     11.00632   31EDB975320ECA86420FDB97542 0ECB975310ECA86420EDB97532F
 5  0  3  7     10.99917   21EDB975320ECA86420FDB97542 0ECB975310ECA86420EDB97532F
 5  0  7  6     10.00177   ECA976420FDB986421FDBA86532 0EDBA86531FECA875310ECA9764
 5  0  7  7      9.98343   ECA976420EDB986421FDBA86532 0EDBA86531FECA875320ECA9764
 5  0 11  5      9.00522   9865320FDCA976320FDCA976432 0EDCA9764310EDA9764310EDBA8
 5  0 11  6      8.99098   9765320FDCA976320FDCA976432 0EDCA9764310EDA9764310EDBA9
 5  0 15  5      8.00034   5321FEDBA9765310FDCA9865431 0FDCBA8764310FDBA9765321FED
 5  0 15  6      7.98004   5321FEDBA9764310FDCA9865431 0FDCBA8764310FDCA9765321FED
 5  1  3  5      7.00530   0FDDBB98764321FEDCA98764321 0FEDCA98764321FEDCA98755331
 5  1  3  6      6.98706   0FDDBB98754321FEDCA98764321 0FEDCA98764321FEDCB98755331
 5  1  7  3      5.99795   CBA987643210FEDCBA987654321 0FEDCBA9876543210FEDCA98765
 6  0  0  0      5.90288   BA9876543210FEDCBA987654321 0FEDCBA9876543210FEDCBA9876
 6  0  0  3      5.84654   BA9876543210FECBB9987654321 0FEDCBA9877554210FEDCBA9876
 6  0  0  8      5.76708   BA9866543210FECBA9876654321 0FEDCBAA987654210FEDCBAA876
 6  0  0 13      5.70068   A98866533210FECBA9876554321 0FEDCBBA987654210FEDDBAA887
 6  0  1  2      5.62021   A9876653211FFECBA9876544321 0FEDCCBA987654211FFEDBAA987
 6  0  1  7      5.53168   A9876543210FEDCBA9876544321 0FEDCCBA9876543210FEDCBA987
 6  0  1 12      5.47233   99765543210FEDCBA9876543321 0FEDDCBA9876543210FEDCBBA97
 6  0  2  1      5.38984   98765442100FEDCBA9876543321 0FEDDCBA98765432100FECCBA98
 6  0  2  6      5.30937   9876543210FFEDBAA9876543221 0FEEDCBA98766532110FEDCBA98
 6  0  2 11      5.23493   8766543210FEDDBAA9876543221 0FEEDCBA98766533210FEDCBAA9
 6  0  3  0      5.14942   8765443210FEDCBA98876543221 0FEEDCBA98876543210FEDCCBA9
 6  0  3  5      5.06795   8755433100FEDCBA98776543221 0FEEDCBA99876543210 0FDDCBB9
 6  0  3 10      4.99752   765543210FFEDCBA98766543221 0FEEDCBAA98765432110FEDCBBA
 6  0  3 15      4.91102   765433210FEDDCAA98766543221 0FEEDCBAA98766433210FEDDCBA
 6  0  4  4      4.84362   754433210FEDCCAA98765543211 0FFEDCBBA98766443210FEDDCCB
 6  0  4  9      4.76516   654432200FEDCBA998765543211 0FFEDCBBA98776543210 0EEDCCB
 6  0  4 14      4.69071   65432210FFEDCBA998765443211 0FFEDCCBA98776543211 0FEEDCB
 6  0  5  3      4.60219   64432210FEDDCBA987765443211 0FFEDCCBA99876543321 0FEEDCC
 6  0  5  8      4.52977   5433211FFEDCCBA987765443211 0FFEDCCBA998765443211FFEDDC
 6  0  5 13      4.45231   5432210FFEDCBBA987665433211 0FFEDDCBAA987655432110FEEDC
 6  0  6  2      4.37184   5322110FEEDCBB9987665433211 0FFEDDCBAA987755432210FFEED
 6  0  6  7      4.29136   4322110FEDDCBA9887655433211 0FFEDDCBBA988765433210FFEED
 6  0  6 12      4.21190   4321000EEDCCBA9887655433211 0FFEDDCBBA98876544322000FED
 6  0  7  1      4.12941   421100FEEDCBBA9877655433211 0FFEDDCBBA998765543221 00FFE
 6  0  7  6      4.06201   321100FEDDCBAA9877654432211 0FFEEDCCBA998766543321 00FFE
 6  0  7  9      4.00668   321100FEDCCBAA8876654432211 0FFEEDCCBAA98866544321 00FFE
 6  0  7 10      3.99159   32110FFEDCCBAA8876654432211 0FFEEDCCBAA988665443211 0FFE
 6  0  7 11      3.97853   32100FFEDCCBAA8876654432211 0FFEEDCCBAA9886654432110 0FE
 6  0  8  0      3.90006   21100FFDDCBBA98876654432211 0FFEEDCCBAA98876554331100FF
 6  0  8  5      3.81758   2100FFEDDCBAA98776654432211 0FFEEDCCBAA99876654332110 0F
 6  0  8 10      3.74615   1000FEEDCCBAA98776554432211 0FFEEDCCBBA998766544322100 0
 6  0  8 15      3.66669   10FFFEEDCBBA998776554332211 0FFEEDDCBBA9987765543221110
 6  0  9  4      3.58219   10FFEEDCCBAA998766554332211 0FFEEDDCBBAA987766544322110
 6  0  9  9      3.51178   0FFEEEDCCBAA988766544332211 0FFEEDDCCBAA988766544322211
 6  0  9 14      3.42527   0FFEDDDCBBA9987766544332211 0FFEEDDCCBAA998776554333211
 6  0 10  3      3.35083   0FEEDDCCBBA9987665544332111 0FFFEDDCCBBAA98776554433221
 6  0 10  8      3.28444   FEEEDDCBBAA9987665544322111 0FFFEEDCCBBAA98776655433222
 6  0 10 13      3.20195   FEEDDCCBBA99887665543322111 0FFFEEDDCBBAA98877655443322
```

```
                                                                            PAGE 3
 THUMBWHEEL         CRCTD                       PHASE SHIFTER STATES
  SWITCH            BEAM                LEFT                              RIGHT
 SETTING            POS.     222222221111111111                    11111111112222222
                             765432109876543210987654321 012345678901234567890123456

  6  0 11  2      3.13154    EEDDCCCBAA99887665443322111 0FFFEEDDCCBAA98877665444332
  6  0 11  7      3.04402    EDDDCCBBAA99876655443322111 0FFFEEDDCCBBAA9877665544333
  6  0 11  9      3.00681    EDDDCCBAAA98876655443322111 0FFFEEDDCCBBAA9887666544333
  6  0 11 10      2.99273    EDDCCCBAAA98876655443322111 0FFFEEDDCCBBAA9887666544433
  6  0 11 12      2.95953    EDCCCCBAA998876655443322111 0FFFEEDDCCBBAA9887766544443
  6  0 12  1      2.88610    DDCCBBBA9998776655443322111 0FFFEEDDCCBBAA9987776555443
  6  0 12  6      2.81368    DCCCBBBA9988776554443322110 00FFEEDDCCCBBA9988776555444
  6  0 12 11      2.74225    DCBBBBAA9988776554433222110 00FFEEEDDCCBBA9988776655554
  6  0 13  0      2.66078    CCBBBBA99887766554433222110 00FFEEEDDCCBBAA998877655554
  6  0 13  5      2.58836    CBBBAAA99887765554433221110 00FFFEEDDCCBBBA998877666555
  6  0 13 10      2.49882    CBBAAAA98877665544433221110 00FFFEEDDCCCBBAA99887666655
  6  0 13 15      2.42842    BBAAAA988877665544333221110 00FFFEEDDDCCBBAA99888766665
  6  0 14  4      2.35297    BAAA99988777665544332221110 00FFFEEEDDCCBBAA99988777666
  6  0 14  9      2.27250    AAA999988776655444332221110 00FFFEEEDDCCCBBAA9988777766
  6  0 14 14      2.18800    AA9999887766655443332221110 00FFFEEEDDDCCBBAAA998877776
  6  0 15  3      2.10753    A99988877766654443332221110 00FFFEEEDDDCCCBAAA999888777
  6  0 15  8      2.04014    998988877766554443322211110 00FFFFEEEDDCCCBBAA999888787
  6  0 15 10      2.00393    998988877666554433322211110 00FFFFEEEDDDCCBBAAA99888787
  6  0 15 11      1.98984    998888877666554433322211110 00FFFFEEEDDDCCBBAAA99888887
  6  0 15 13      1.95462    998888777665554433322211110 00FFFFEEEDDDCCBBBAA99988887
  6  1  0  2      1.88823    988877776665554433322211100 000FFFEEEDDDCCBBBAAA9999888
  6  1  0  7      1.80876    888877766665544333222211100 000FFFEEEEDDDCCBBAAAA999888
  6  1  0 12      1.72928    887777766655543333222111100 000FFFFEEEDDDDCBBBAAA999998
  6  1  1  1      1.64377    877777666555443332222111100 000FFFFEEEEDDDCCBBBAAA99999
  6  1  1  6      1.56933    777766665554443332222111100 000FFFFEEEEDDDCCCBBBAAAA999
  6  1  1 11      1.49186    776666655554443322221111100 000FFFFFEEEEDDCCCBBBBAAAAA9
  6  1  2  0      1.41742    766656655544433322221111000 0000FFFFEEEEDDDCCCBBBAABAAA
  6  1  2  5      1.34197    666656555444433222211111000 0000FFFFFEEEEDDCCCCBBBABAAA
  6  1  2 10      1.26450    655555555444333222211111000 0000FFFFFEEEEDDDCCCBBBBBBBB
  6  1  2 15      1.18402    555555544443332222211111000 0000FFFFFEEEEEDDDCCCCBBBBBB
  6  1  3  4      1.10857    555545444433332222211110000 00000FFFFFEEEEDDDDCCCCBCBBB
  6  1  3  9      1.03010    544445444333332221111110000 00000FFFFFFEEEDDDDDCCCBCCCC
  6  1  3 11       .99791    544444443333332221111110000 00000FFFFFFEEEDDDDDDCCCCCCC
  6  1  3 14       .95264    444444443333322211111110000 00000FFFFFFFEEEDDDDDCCCCCCC
  6  1  4  3       .87216    443444433333222111111100000 000000FFFFFFFEEEDDDDDCCCCDC
  6  1  4  8       .78766    433434333332221111111100000 000000FFFFFFFFEEEDDDDDCDCDD
  6  1  4 13       .72026    333333333322221111111000000 0000000FFFFFFFEEEEDDDDDDDDD
  6  1  5  2       .64079    332333322222221111110000000 00000000FFFFFFEEEEEEEDDDDED
  6  1  5  7       .56132    322223322222211111100000000 000000000FFFFFFEEEEEEDDEEEE
  6  1  5 12       .48688    222222222222111111000000000 0000000000FFFFFFEEEEEEEEEEE
  6  1  6  1       .39836    222212222211111100000000000 000000000000FFFFFFEEEEEFEEE
  6  1  6  6       .31084    211212222111110000000000000 00000000000000FFFFFEEEEFEFF
  6  1  6 11       .24043    111112111111110000000000000 00000000000000FFFFFFFFEFFFF
  6  1  7  0       .14788    111111111100000000000000000 000000000000000000FFFFFFFFF
  6  1  7  5       .06639    110101100000000000000000000 000000000000000000000FF0F0F
  7  0  0  0       .00000    000000000000000000000000000 000000000000000000000000000
  7  0  0  1      -.01901    000000000000000F00000000000 000000000000100000000000000
  7  0  0  5      -.08907    00000000000000FFFF0F0000000 000000001011110000000000000
  7  0  0 10      -.15612    F0F0F000000000FFFFFFF000000 000000011111110000000001010
  7  0  0 15      -.23220    FFFFF00FF00000FFFFFFFF00000 000000111111110000011001111
  7  0  1  4      -.32029    FFFFF00FFFFF0FFFFFFFFFF0000 000001111111111011111001111
  7  0  1  9      -.38537    EFFFFFFFFFFFFFFFFFFFFFFF000 000011111111111111111111111
  7  0  1 14      -.45948    EEEEEFFEFFFFFFFFFFFFFFFF000 000011111111111111112112222
  7  0  2  3      -.54560    EEEEEEEEEEFFFFEFFFFFFFFF000 000011111111121111222222222
  7  0  2  8      -.61773    DEEEEEEEEEEEFFEEFFFFFFFFF00 000111111111122112222222222
  7  0  2 13      -.69887    DDDEDEEEEEEEEFEEEFFFFFFFF00 000111111111222122222223233
  7  0  3  2      -.78204    DDDDDDEEEEEEEEEEEEEFFFFFF00 000111111222222222222233333
```

```
THUMBWHEEL       CRCTD                          PHASE SHIFTER STATES
 SWITCH          BEAM                  LEFT                                RIGHT
SETTING          POS.      222222221111111111                           1111111111222222
                           765432109876543210987654321 012345678901234567890123456

  7  0  3  7    -.85318    CDCDDDDDEEEEEEEEEEEFFFFFF00 000111111222222222233333343
  7  0  3 12    -.93437    CCCCDDDDDDDEEEEEEEEEFFFFF00 000111112222222223333333444
  7  0  4  0   -1.00252    CCCCCDDDDDDDEEDEEEEEEFFFF00 000111122222232233333334444
  7  0  4  1   -1.02157    CCCCCDDDDDDDDEDEEEEEEFFFF00 000111122222232333333334444
  7  0  4  6   -1.07670    BBBCCCDDDDDDDEDEEEEEEFFFFF0 001111122222232333333344455
  7  0  4 11   -1.16594    BBBCCCCCCDDDDDDDEEEEEFFFFF0 001111122222333333344444455
  7  0  5  0   -1.24416    BBBBBCCCCCDDDDDDDEEEEEFFFF0 001111222223333333444445555
  7  0  5  5   -1.32841    BAABBCCCCCCCDDDDDDEEEEFFFF0 001111222233333344444445566
  7  0  5 10   -1.39761    AAAABBBBCCCCDDDDDDEEEEFFFF0 001111222233333334444555666
  7  0  5 15   -1.47687    AAAAABBBBCCCCDDDDDDEEEEFFF0 001112222333333444445555666
  7  0  6  4   -1.56316    A99AABBBBBCCCCCDDDDEEEEFFF0 001112272333344444555556677
  7  0  6  9   -1.63841    9999ABBBBBBCCCCCDDDDEEEFFF0 001112223333444445555556777
  7  0  6 14   -1.72272    99999ABABBBBCCCCCDDDEEEFFF0 001112223334444455555656 7777
  7  0  7  3   -1.79098    88899AAAABBBCCCCCDDDEEEFFF0 001112223334444455566667788
  7  0  7  8   -1.86929    88899AAAAABBBCCCCCDDDEEEFF0 001122233344444555666667788
  7  0  7 13   -1.94057    778899AAAABBBCBCCCDDDEEEFF0 001122233344454555666677889
  7  0  8  0   -1.99580    778899A9AAABBBBCCCDDDEEEFF0 001122233344455556667677889
  7  0  8  1   -2.00986    778889A9AAABBBBCCCDDDEEEFF0 001122233344455556667678889
  7  0  8  2   -2.02593    77888999AAABBBBCCCDDDEEEFF0 001122233344455556667778839
  7  0  8  7   -2.11330    777889999AAABBBBCCCDDEEEFF0 001122233444555566677778899
  7  0  8 12   -2.17659    667788999AAABBBBCCCDDDEEFF0 00112233344455556667778899A
  7  0  9  1   -2.25896    6667788999AAABBBCCCDDDEEFF0 0011223334445556667778899AA
  7  0  9  6   -2.33532    5667788899AABBBBCCCDDEEFF0 0011223344455556677788899AA
  7  0  9 11   -2.41873    55667788999AAAABBCCCDDEEFF0 001122334445566667778899AAB
  7  0 10  0   -2.50214    555667888999AAABBBCCDDEEFF0 001122334455566677788889AABB
  7  0 10  5   -2.56949    45566778889 9AAAABBCCDDEEEF0 0012223344556666778889 9AABB
  7  0 10 10   -2.64489    44556777889 99AAABBCCDDDEEF0 001223334455666777888999ABBC
  7  0 10 15   -2.72432    444566777889 9AAABBCCCDDEEF0 001223344455666778899 9AABCC
  7  0 11  4   -2.80175    3445567778899A9AABBCCDDEEF0 0012233445566767788999ABBCC
  7  0 11  9   -2.88823    33455666788899 9AABBCCDDEEF0 001223344556677788889AAABBCD
  7  0 11 14   -2.96368    3334456677889 99AABBCCDDEEF0 001223344556677788899AABCCDD
  7  0 12  1   -3.00895    2334456667888999AABBCCDDEEF0 00122334455667788889AAABCCDD
  7  0 12  3   -3.03007    23344566677889 9AABBCCDDEEFF 01122334455667788899AAABCCDD
  7  0 12  8   -3.11157    22334566677888999AABBCDDEEFF 01122334556677788899AAABCDDE
  7  0 12 13   -3.18905    22234555677789 99AABBCCDEEFF 01122344556677789 99ABBBCDEE
  7  0 13  2   -3.26957    122344556677888 9AABBCCDEEFF 0112234455667888 99AABBCCDEE
  7  0 13  7   -3.34002    1122345566778889 9ABBCCDDEFF 0112334455677888 99AABBCDEEF
  7  0 13 12   -3.42862    11223445566778899AABCCDDEFF 0112334456677889 9AABBCCDEEF
  7  0 14  1   -3.49708    01122344566778899AABCCDDEFF 01123344566778899AABCCDEEFF
  7  0 14  6   -3.58166    00122344556678889AABBCDDEFF 01123345566788 89AABBCCDEEF0
  7  0 14 11   -3.65518    F0012344556677889 9ABBCDDEFF 011233455677889 9AABBCCDEF00
  7  0 15  0   -3.74180    FF012334455677789 9ABBCDDEFF 0112334556778999ABBCCDDEF01
  7  0 15  5   -3.81334    FF011233455677789 9AABCCDEFF 0112344566778999ABBCDDEFF01
  7  0 15 10   -3.89192    EFF1123344566778 89AABCCDEFF 011234456678899AABCCDDEFF11
  7  0 15 15   -3.97356    EEF01223345567788 9AABCCDEFF 0112344566788 99ABBCDDEEF012
  7  1  0  2   -4.00782    EEF0012334556778 89AABCCDEEF 01223445667889 9ABBCDDEF0012
  7  1  0  4   -4.04411    EEF0012234556777 89AABCCDEEF 0122344566789 99ABBCDEEF0012
  7  1  0  9   -4.12072    DEE001223445667789 9ABCCDEEF 01223445677899AABCCDEEF0022
  7  1  0 14   -4.20138    DDEF0122344556678 99ABBCDEEF 012234556778 9AABBCCDEEF0123
  7  1  1  3   -4.27801    CDEF01122345566788 9ABBCDEEF 0122345567889AABBCDEEFF0123
  7  1  1  8   -4.35869    CDEEF01123445667889ABBCDEEF 0122345567889AABCCDEFF01223
  7  1  1 13   -4.43838    CCDEF0112334566778 9AABCDEEF 012234566789 9AABCDDEFF01234
  7  1  2  2   -4.50193    BCDEE0012334556778 9AABCDDEF 012334566789 9ABBCDDEF002234
  7  1  2  7   -4.58971    BCCEE00122344566789 9ABCDDEF 0123345677 89AABCCDEEF002244
  7  1  2 12   -4.67043    BBCDEF0112344556789 9ABCDDEF 0123345677 89ABBCCDEFF012345
  7  1  3  1   -4.74915    ABCDEF0012234556788 9ABCDDEF 012334567889ABBCDEEF0012345
  7  1  3  6   -4.82081    ABBDDFF0112345567889ABCCDEF 01234456 7889ABBCDEFF0113355
```

```
                                                                         PAGE 5
 THUMBWHEEL       CRCTD                       PHASE SHIFTER STATES
 SWITCH           BEAM                 LEFT                           RIGHT
SETTING           POS.      222222221111111111                  1111111111222222
                            765432109876543210987654321 0123456789012345678901234567

  7  1  3 11    -4.90056    AABCDEF0012345567789ABCCDEF 0123445678 99ABBCDEF00123456
  7  1  4  0    -4.98233    9ABCDEFF01233456678 9ABCCDEF 01234456789AABCDDEF01123456
  7  1  4  2    -5.00758    9AACDEFF0123345667 89ABBCDEF 0123455678 9AABCDDEF01123466
  7  1  4  5    -5.06109    9AACCEFF0122345567 89ABBCDEF 0123455678 9ABBCDEEF01124466
  7  1  4 10    -5.14390    99ABCEEF0112344567 89ABBCDEF 0123455678 9ABCCDEFF01224567
  7  1  4 15    -5.21561    89ABCDEFF012344567 89AABCDEF 0123456678 9ABCCDEF011234567
  7  1  5  4    -5.29036    899BBDEEF012344567 889ABCDEF 0123456788 9ABCCDEF012235577
  7  1  5  9    -5.35299    789ABDDEF012334567 889ABCDEF 0123456788 9ABCDDEF012335678
  7  1  5 14    -5.45100    789ABCDEF011234566 789ABCDEF 0123456789 AABCDEFF012345678
  7  1  6  3    -5.53690    788AACDEF001234456 789ABCDEF 0123456789 ABCCDEF0012346688
  7  1  6  8    -5.61473    678AACDEEF01233456 789ABCDEF 0123456789 ABCDDEF0122346689
  7  1  6 13    -5.69560    6789ABCDEF01223456 789ABCDEF 0123456789 ABCDEEF0123456789
  7  1  7  2    -5.79063    6789ABCDDEF0123456 789ABCDEF 0123456789 ABCDEF01233456789
  7  1  7  7    -5.85838    56799BCCDEF0123456 789ABCDEF 0123456789 ABCDEF0123445779A
  8  0  0  0    -5.90288    56789ABCDEF0123456 789ABCDEF 0123456789 ABCDEF0123456789A
  8  0  0  5    -5.99243    56789ABCDEF0122345 779ABCDEF 0123456799 BCDEEF0123456789A
  8  0  0  6    -6.00652    56789ABCDEF0122345 778ABCDEF 0123456899 BCDEEF0123456789A
  8  0  4  7    -7.00557    01245689ABCDE00134 5679ABCDF 01345679AB CDF002345678ABCEF
  8  0  8  5    -7.99606    CDE01345789ACDEF12 45689ACDF 0134678ABC EF12346789BCDF023
  8  0  8  6    -8.01431    CDE01345689ACDEF12 45689ACDF 0134678ABC EF1234678ABCDF023
  8  0 12  5    -8.99417    79ACDF1235689BCDF0 24578ABDE 0235689BCE 0134578ABDEF13467
  8  0 12  6    -9.00942    78ACDF1235689BCDF0 24578ABDE 0235689BCE 0134578ABDEF13468
  8  1  0  6   -10.01121    24689BDE024578ABDF 124679BCE 024579ACEF 135689BCE023578AC
  8  1  4  4   -11.00033    E01468ABDF124689BD F13568ACE 02468ABDF1 3578ACEF13568ACF0
  9  0  0  0   -11.86961    ACE02468ACE02468AC E02468ACE 02468ACE02 468ACE02468ACE024
  9  0  0  7   -11.99234    ACE02468ACE024579B DF1468ACE 02468ACF13 579BCE02468ACE024
  9  0  0  8   -12.00769    ACE01468ACE024579B DF1468ACE 02468ACF13 579BCE02468ACF024
  9  0  4  7   -12.99161    579CE03579BDF2358A CE03579BE 02579BD024 68BDE13579BD02479
  9  0  4  8   -13.00910    579CE03479BDF2358A CE03579BE 02579BD024 68BDE13579CD02479
  9  0  8  5   -14.00152    1358ADF1468ADF1368 BDF2469BE 0257ACE135 8ADF1368ACF1368BD
  9  0 12  4   -15.00352    CF1469CE0358ADF147 9CE1368BD 0358ADF247 9CF1368BD0247ACF1
  9  1  0  2   -15.99645    8AD0258BD0358BD025 8AD0258AD 0368BE0368 BE0358BD0358BE036
  9  1  0  3   -16.01632    8AD0258BD0358BDF25 8AD0258AD 0368BE0368 BE1358BD0358BE036
  9  1  4  0   -17.00970    369CF257AD0358BE03 69CF247AD 0369CE147A D0258BD0369BE147A
 10  0  0  0   -17.97052    F258BE147AD0369CF2 58BE147AD 0369CF258B E147AD0369CF258BE
 10  0  0  1   -17.99051    F258BE147AD0369BF2 58BE147AD 0369CF258B E157AD0369CF258BE
 10  0  0  2   -18.00840    F258BE147AD0369BF1 58BE147AD 0369CF258B F157AD0369CF258BE
 10  0  3 14   -18.99159    BE147BE147AD147AD0 36AD036AD 036AD036AD 0369CF369CF259CF2
 10  0  3 15   -19.01173    BE147BE147AD146AD0 36AD036AD 036AD036AD 036ACF369CF259CF2
 10  0  7 11   -19.99802    7AD047BE148BE248BE 258CF269D 037AE148BE 258CE258CF259C036
 10  0  7 12   -20.01510    79D047BE148BE248BE 258CF269D 037AE148BE 258CE258CF259C037
 10  0 11  7   -20.99380    259D047BE259CF269D 047BE259D 037BE259C0 37AE147BE259C037B
 10  0 11  8   -21.01532    259D047BE258CF269D 047BE259D 037BE259C0 37AE148BE259C037B
 10  0 15  3   -21.99929    E159C047BF26AD048B F36AE159C 047BF26AD1 58C036AE159C047BF
 10  0 15  4   -22.01013    E159C047BF26AD048B F36AD159C 047BF36AD1 58C036AE159C047BF
 10  1  2 14   -22.99082    AD159D148C037BE26A E159D148C 048CF37BF2 6AE259D048CF37BF3
 10  1  2 15   -22.99847    9D159D148C037BE26A E159D148C 048CF37BF2 6AE259D048CF37BF3
 10  1  3  0   -23.01596    9D159D148C037BE26A D159D148C 048CF37BF3 6AE259D048CF37BF3
 10  1  6  9   -23.99439    59D25AE159D159C048 C048C048C 048C048C04 8C047BF37BF26BE37
 10  1  6 10   -24.00781    59D15AE159D159C048 C048C048C 048C048C04 8C047BF37BF26BF37
 11  0  0  0   -24.29094    48C048C048C048C048 C048C048C 048C048C04 8C048C048C048C048
 11  0  2 10   -25.00143    159E26AE26AE37AE37 BF37BF38C 048D159D15 9D269D26AE26AE27B
 11  0  6  3   -25.99762    E15AE37BF48C048D15 9E26AF37C 049D16AE27 BF38C048C159D26BF
 11  0  6  4   -26.01772    E15AE37BF38C048D15 9E26AF37C 049D16AE27 BF38C048D159D26BF
 11  0  9 12   -26.99227    9D26BF48C15AE26BF4 8C15AE37C 049D26BF48 C15AE26BF48C15AE3
 11  0  9 13   -27.01481    9D26BF48C159E26BF4 8C15AE37C 049D26BF48 C15AE27BF48C15AE3
 11  0 13  6   -27.99445    59E37C15AE37C049D2 7B049D27B 059E37C059 E37C049D26BF49D27
```

```
                                                   PHASE SHIFTER STATES
 THUMBWHEEL        CRCTD                                                        RIGHT
  SWITCH           BEAM                LEFT                              1111111111222222
 SETTING           POS.       22222222111111111
                              765432109876543210987654321 0123456789012345678901234566

 11  0 13  7   -28.01038      59E27C15AE37C049D27B049D27B 059E37C059E37C049D26BF49E27
 11  1  0 15   -29.00909      15AF49E27B059E27C15AF38D26B 05AE38D16BF49E27B059E27C16B
 11  1  4  7   -30.00759      D16C06AF49E27C15AF49E37C16B 05AF49D27C16BF49E27C16A04AF
 12  0  0  0   -30.94485      9E38D27C16B05AF49E38D27C16B 05AF49E38D27C16B05AF49E38D2
 12  0  0  3   -31.01021      9E38D27C16B05AE39D38D27C16B 05AF49E38D37D26B05AF49E38D2
 12  0  3 10   -32.00157      5AF5AF49E39E38D27C16C16B06B 05A05AF4AF49E38D27D27C16B16
 12  0  6 15   -32.99310      27C16C16C16B16B05B05B05B05B 05B05C05B05B05AF5AF4AF4AF49
 12  0  7  0   -33.00985      26C16C16C16B16B05B05B05B05B 05B05B05B05B05AF5AF4AF4AF4A
 12  0 10  5   -33.98970      D38E39E49E49F49E49F4AF5AF5B 05B16B16C17C27C17C27C27D28D
 12  0 10  6   -34.00787      D28E39E49E49F49E49F4AF5AF5B 05B16B16C17C27C17C27C27D28E
 12  0 13 10   -34.99160      AF5A06C16C17C27D28E39E49F5A 06B17C27D28E39E49F4AF4A06B1
 12  0 13 11   -35.01001      AF5A06B16C17C27D28E39E49F5A 06B17C27D28E39E49F4AF5A06B1
 12  1  0 15   -36.00040      6B17D39E49F5A05B17C28D39F4A 06C17D38E49F5B06B17C27D39F5
 12  1  4  3   -37.00134      28D4A06B17D38E49F5B17D28E4A 06C28E39F5B17C28D39F5A06C38
 12  1  7  4   -37.99922      F5B16D38E4A06C28E4A06C28E4A 06C28E4A06C28E4A06C28D3AF5B
 12  1  7  5   -38.01709      F5A16D38E4A06C28E4A06C28E4A 06C28E4A06C28E4A06C28D3AF6B
 13  0  0  0   -38.10141      E4A06C28E4A06C28E4A06C28E4A 06C28E4A06C28E4A06C28E4A06C
 13  0  2 13   -38.99500      B17E3A06C28E4B06C39F5B17D4A 06C39F5B17D4A05C28E4A06D29F
 13  0  2 14   -39.01950      B17E3A06C28E4A06C39F5B17D4A 06C39F5B17D4A06C28E4A06D29F
 13  0  5 15   -40.00307      8E4A07D3906C29F5B17E4A07D3A 06D3906C29F5B17E4A07D3906C2
 13  0  8 15   -40.99140      4A07E4B17D4A07D3A06D3906D3A 06D3A07D3A06D3906C39F5C2906
 13  0  9  0   -41.01002      4A07D4B17D4A07D3A06D3906D3A 06D3A07D3A06D3906C39F5C3906
 13  0 11 15   -41.99562      17D4A18E4B28F5B28F5C29F6C3A 06D4A17E4B18E5B18E5C28F6C39
 13  0 12  0   -42.00508      07D4A18E4B28F5B28F5C29F6C3A 06D4A17E4B18E5B18E5C28F6C39
 13  0 14 15   -43.00424      D4A18F5C29F6D3907D4B18F5C39 07D4B18F5C3907D3A17E4B18F6C
 13  1  1 14   -44.00934      A07E5C3907D4B18F5C3A07E5C29 07E4B2906D4B18F5C3907D4B290
 13  1  4 12   -44.99652      6D4B2A07E5B2906D4B2906D4B29 07E5C3A07E5C3A07E5B2906E5C3
 13  1  4 13   -45.01786      6D4B2907E5B2906D4B2906D4B29 07E5C3A07E5C3A07E5B2907E5C3
 13  1  7  7   -45.98231      3A19F7E4B2907E5C3A18F6D4B29 07E5C3A18F6D4B2907E5C2917F6
 13  1  7  8   -46.00258      3A18F7E4B2907E5C3A18F6D4B29 07E5C3A18F6D4B2907E5C2918F6
 13  1  7  9   -46.02576      3A18F7D4B2907E5C3A18F6D4B29 07E5C3A18F6D4B2907E5C3918F6
```

```
CORRECTED BEAM ANGLES FOR SCAN PROGRAM 1
DATE: 07/01/84
FREQUENCY= 5060 MHZ

                                                                  PAGE 1
 THUMBWHEEL      CRCTD                    PHASE SHIFTER STATES
 SWITCH          BEAM               LEFT                             RIGHT
SETTING          POS.     222222221111111111                  1111111112222222
                          765432109876543210987654321 0123456789012345678901234567890123456

 0  0  0  0   45.69483    D6F81A3C5E7092B4D6F81A3C5E7 092B4D6F81A3C5E7092B4D6F81A
 0  0  0  1   45.66777    D6F81A3C5E7092B3D6F81A3C5E7 092B4D6F81A3D5E7092B4D6F81A
 0  0  0  2   45.64358    D6F81A3C5E7092B3D5F81A3C5E7 092B4D6F81B3D5E7092B4D6F81A
 0  0  0  3   45.61512    D6F81A3C5E7092A3D5F81A3C5E7 092B4D6F81B3D6E7092B4D6F81A
 0  0  2  0   44.99397    B4D6F92A3C6F81A3C5E7092B5E7 092B5E7092B4D6F81A4D6E71A3C
 0  0  4 14   44.00244    81A3C6F81B4D6F81B4D6F82B4D7 093C5E81A3C5F81A3C5F81A4D6F
 0  0  4 15   43.97751    81A3C6F81A4D6F81B4D6F82B4D7 093C5E81A3C5F81A3C6F81A4D6F
 0  0  7 12   43.00714    5D70A3D6F82B4E6092C5E81A4D7 093C6F82B4E70A2C5E81A3D6093
 0  0  7 13   42.99759    4D70A3D6F82B4E6092C5E81A4D7 093C6F82B4E70A2C5E81A3D6093
 0  0 10 12   42.00267    1A4D70A3D6F92C5E81B4E70A3D7 093D6092C5F82B4E71A3D6093C6
 0  0 10 13   41.98386    1A4D70A3D6F92C5E81B4D70A3D7 093D6093C5F82B4E71A3D6093C6
 0  0 13 12   41.00913    E71A4E71A4D70A3D6093D6093D6 0A3D70A3D70A3D6093C6F92C6F9
 0  0 13 13   40.99061    E70A4E71A4D70A3D6093D6093D6 0A3D70A3D70A3D6093C6F92C609
 0  1  0 14   40.00106    A3D71B5E82B5E81B5F82C5F93C6 0A4D71B4E81B5F82B5E82B5F93D
 0  1  0 15   39.97757    A3D71B5E81B5E81B5F82C5F93C6 0A4D71B4E81B5F82B5F82B5F93D
 0  1  4  0   38.99820    60A4E82B5F93C60A3D71B5F82C6 0A4E81B5F93D60A4D71B5E82C60
 0  1  7  1   37.99904    3D71B5F93C60A4E82C60A4E82C6 0A4E82C60A4E82C60A4D71B5F93
 1  0  0  0   37.83552    2C60A4E82C60A4E82C60A4E82C6 0A4E82C60A4E82C60A4E82C60A4
 1  0  2 11   37.00343    F93E82C60A4E83C61B5F93D71C6 0A4F93D71B5FA4D82C60A4E82D7
 1  0  2 12   36.97974    F93E82C60A4E83C60B5F93D71C6 0A4F93D71B50A4D82C60A4E82D7
 1  0  5 15   35.99936    C60A4F93D82C61B5F93E82C71B6 0A5F94E82D71B5FA4E83D71C60A
 1  0  9  3   35.00198    82C71C60B50A4F93D82D71C61B6 0A5FA4F93E83D71C60B50A4F94E
 1  0  9  4   34.97884    82C71C60B5FA4F93D82D71C61B6 0A5FA4F93E83D71C61B50A4F94E
 1  0 12  9   33.99888    4E93E93E83D82D71C61B61B60B5 0B50A5FA5FA4F93E83D82D72D72
 1  0 15 14   33.00798    0B50B60B50B50B50A50A50A50B5 0B50B60B60B60B50B50B50A50B5
 1  0 15 15   32.99130    0A50B60B50B50B50A50A50A50B5 0B50B60B60B60B50B50B50A50B6
 1  1  3  6   31.99568    C71D73D83D83E93E94E94FA4FA5 0B61C61C72C72D72D83D83D93F9
 1  1  6 12   31.00237    83E94FA50B61C71C72D83E94FA5 0B61C72D83E94F94FA50B61C72D
 1  1  6 13   30.98021    83E94FA50B61C61C72D83E94FA5 0B61C72D83E94FA4FA50B61C72D
 2  0  0  0   30.74140    72D83E94FA50B61C72D83E94FA5 0B61C72D83E94FA50B61C72D83E
 2  0  2 10   29.99736    4FA61C72D83EA5FA61C72D83EA5 0B62D83E94FA61B62D83E94FA61
 2  0  6  1   29.01046    1B72D94FA61C73D94FA61C73E95 0B72D94FA61C73D94FA61C73E95
 2  0  6  2   28.99336    1B62D94FA61C73D94FA61C73E95 0B72D94FA61C73D94FA61C73EA5
 2  0  9 10   28.00012    C73EA61C83EA50B72E940B72E95 0B72E950C72E950B62D84FA62D9
 2  0  9 11   27.98316    C73EA51C83EA50B72E940B72E95 0B72E950C72E950B62D84FB62D9
 2  0 13  4   26.99823    83FB62E950C73E951C83FA62D94 0C73EA61D84FB72D940B72EA51D
 2  1  0 14   25.99777    4FB73FB62E950C73FB62E951D84 0C83FB72EA51D940B72EA51D951
 2  1  4  8   24.99863    0B74FC73FB72EA51D951D940C84 0C840C73FB73FB62E951D941C95
 3  0  0  0   24.13771    C840C840C840C840C840C840C84 0C840C840C840C840C840C840C8
 3  0  0  7   24.00697    C840C840C840C83FB73FB840C84 0C840C851D951D840C840C840C8
 3  0  0  8   23.99063    C840B840C840C83FB73FB840C84 0C840C851D951D840C840C850C8
 3  0  4  4   22.99397    83FC851D951D961EA62EA73FB74 0C951D962EA62FA73FB73FB841D
 3  0  7 15   22.00006    3FC851EA62EB73FC841D962EB74 0C952EA73FC841D952EA62FB841
 3  0  8  0   21.98176    3FC851E962EB73FC841D962EB74 0C952EA73FC841D952EA72FB841
 3  0 11 11   20.99487    FB841EA63FC851DA63FC851EA74 0C962FB841DA63FB841DA62FC85
 3  0 15  8   20.00408    A731DA730D962FB851EA740DA73 0D9630C962FB851EA730D963FD9
 3  0 15  9   19.98493    A731DA730D962FB841EA740DA73 0D9630C962FC851EA730D963FD9
 3  1  3  6   18.98918    63FD9730D9630D9630C9630C963 0DA740DA740DA730DA730D9731D
 3  1  7  1   17.99596    2FC9630DA630DA741EB852FC963 0DA741EB852FC9630DA630DA741
 4  0  0  0   17.86037    1EB852FC9630DA741EB852FC963 0DA741EB852FC9630DA741EB852
 4  0  3  5   16.99444    EB752FD9641EB852FC9741EB863 0DA852FC9741EB852FCA731EB95
 4  0  7  2   16.00581    A631EC9631EB9630DB8530DB853 0DB8530DB8530DA752FDA742FDA
 4  0  7  3   15.99958    9631EC9631EB9630DB8530DB853 0DB8530DB8530DA752FDA742FDA
 THUMBWHEEL        CRCTD                    PHASE SHIFTER STATES
 SWITCH            BEAM              LEFT                             RIGHT
SETTING            POS.    222222221111111111                    11111111112222222
                           765432109876543210987654321 012345678901234567890123456

 4  0 11  1     15.00538   52FDA8630EB9641EC9641FCA753 0DB9641FCA742FCA7520DA8631E
 4  0 11  2     14.99711   42FDA8630EB9641EC9641FCA753 0DB9641FCA742FCA7520DA8631E
 4  0 14 15     14.00972   0EB97520DB8641ECA7530EC9752 0EB97420DB9642FCA8530EB9752
 4  0 15  0     13.99427   0DB97520DB8641ECA7530EC9752 0EB97420DB9642FCA8530EB9753
 4  1  2 15     13.00327   B97531FCA8631FCA8641FDB9642 0ECA7531FCA8641FDA8641FDB97
 4  1  3  0     12.98685   B97531FCA8631FCA8631FDB9642 0ECA7531FDA8641FDA8641FDB97
 4  1  6 13     12.00772   7531FDB97531FCA86420ECA8642 0ECA86420ECA8641FDB97531FDB
 4  1  6 14     11.98728   7531FDB97531ECA86420ECA8642 0ECA86420ECA8642FDB97531FDB
 5  0  0  0     11.79822   6420ECA86420ECA86420ECA8642 0ECA86420ECA86420ECA86420EC
 5  0  3  2     11.00518   31FDB986420ECA86420FDB97542 0ECB975310ECA86420ECA87531F
 5  0  3  3     10.99098   31EDB986420ECA86420FDB97542 0ECB975310ECA86420ECA87532F
 5  0  7  2      9.99150   FCA976420FDBA86421FDCA87532 0EDB986431FECA865310ECA9764
 5  0 11  3      8.98677   9865321FDCA976420FDCA976432 0EDCA9764310ECA976431FEDBA8
 5  0 15  1      8.00709   53210FDBA9765310FDCB9875431 0FDCB98754310FDBA9765310FED
 5  0 15  2      7.99296   5321FFDBA9765310FDCB9875431 0FDCB98754310FDBA9765311FED
 5  1  3  2      7.00185   0FEDBBA8764321FEDCA98765321 0FEDBA98764321FEDCA98655321
 5  1  3  3      6.98573   0FEDB898764321FEDCA98765321 0FEDBA98764321FEDCA98755321
 5  1  7  1      5.99745   CBA987654210FEDCBA987654321 0FEDCBA9876543210FECBA98765
 6  0  0  0      5.86776   BA9876543210FEDCBA987654321 0FEDCBA9876543210FEDCBA9376
 6  0  0  3      5.81176   BA9876543210FECBB9987654321 0FEDCBA9877554210FEDCBA9876
 6  0  0  8      5.73277   BA9866543210FECBA9876654321 0FEDCBAA987654210FEDCBAA876
 6  0  0 13      5.66677   A98866533210FECBA9876554321 0FEDCBBA987654210FEDDBAA887
 6  0  1  2      5.58678   A9876653211FFECBA9876544321 0FEDCCBA987654211FFEDBAA987
 6  0  1  7      5.49878   A9876543210FEDCBA9876544321 0FEDCCBA9876543210FEDCBA987
 6  0  1 12      5.43979   99765543210FEDCBA9876543321 0FEDDCBA9876543210FEDCBBA97
 6  0  2  1      5.35779   98765442100FEDCBA9876543321 0FEDDCBA98765432100FECCBA98
 6  0  2  6      5.27780   987654321 0FFEDBAA9876543221 0FEEDCBA98766532110FEDCBA98
 6  0  2 11      5.20381   87665432 10FEDDBAA9876543221 0FEEDCBA98766533210FEDCBAA9
 6  0  3  0      5.11881   87654432 10FEDCBA98876543221 0FEEDCBA98876543210FEDCCBA9
 6  0  3  5      5.03782   8755433100FEDCBA98776543221 0FEEDCBA998765432100FDDCBB9
 6  0  3  8      4.99982   7755432100FEDCBA98766543221 0FEEDCBAA98765432100FEDCBB9
 6  0  3 10      4.96782   765543210FFEDCBA98766543221 0FEEDCBAA98765432110FEDCBBA
 6  0  3 15      4.88183   765433210FEDDCAA98766543221 0FEEDCBAA98766433210FEDDCBA
 6  0  4  4      4.81483   754433210FEDCCAA98765543211 0FFEDCBBA98766443210FEDDCCB
 6  0  4  9      4.73684   654432200FEDCBA998765543211 0FFEDCBBA98776543210 0EEDCCB
 6  0  4 14      4.66284   654322 10FFEDCBA998765443211 0FFEDCCBA98776543211 0FEEDCB
 6  0  5  3      4.57485   64432210FEDDCBA987765443211 0FFEDCCBA998765433210FEEDCC
 6  0  5  8      4.50286   5433211FFEDCCBA987765443211 0FFEDCCBA998765443211FFEDDC
 6  0  5 13      4.42586   5432210FFEDCBBA987665433211 0FFEDDCBAA987655432110FEEDC
 6  0  6  2      4.34587   5322110FEEDCBB9987665433211 0FFEDDCBAA987755432210FFEED
 6  0  6  7      4.26587   4322110FEDDCBA9887655433211 0FFEDDCBBA988765433210FFEED
 6  0  6 12      4.18688   4321000EEDCCBA9887655433211 0FFEDDCBBA988765443220 00FED
 6  0  7  1      4.10489   421100FEEDCBBA9877655433211 0FFEDDCBBA998765543221 00FFE
 6  0  7  6      4.03789   321100FEDDCBAA9877654432211 0FFEEDCCBA998766543321 00FFE
 6  0  7  8      4.00289   321100FEDCCBAA9876654432211 0FFEEDCCBAA98766544321 00FFE
 6  0  7  9      3.98289   321100FEDCCBAA8876654432211 0FFEEDCCBAA98866544321 00FFE
 6  0  7 11      3.95490   32100FFEDCCBAA8876654432211 0FFEEDCCBAA98866544321100FE
 6  0  8  0      3.87690   21100FFDDCBBA98876654432211 0FFEEDCCBAA98876554331100FF
 6  0  8  5      3.79491   2100FFEDDCBAA98776654432211 0FFEEDCCBAA99876654332 1100F
 6  0  8 10      3.72391   1000FEEDCCBAA98776554432211 0FFEEDCCBBA998766544322 1000
 6  0  8 15      3.64492   10FFFEEDCBBA998776554332211 0FFEEDDCBBA998776554322 1110
 6  0  9  4      3.56092   10FFEEDCCBAA998766554332211 0FFEEDDCBBAA98776654432 2110
 6  0  9  9      3.49093   0FFEEEDCCBAA988766544332211 0FFEEDDCCBAA98876654432 2211
 6  0  9 14      3.40494   0FFEDDDCBBA9987766544332211 0FFEEDDCCBAA99877655433 3211
 6  0 10  3      3.33094   0FEEDDCCBBA9987665544332111 0FFFEDDCCBBAA9877655443 3221
 6  0 10  8      3.26495   FEEEDDCBBAA9987665544322111 0FFFEEDCCBBAA9877665543 3222
 6  0 10 13      3.18295   FEEDDCCBBA99887665543322111 0FFFEEDDCBBAA9887765544 3322
 THUMBWHEEL      CRCTD                      PHASE SHIFTER STATES
  SWITCH         BEAM                 LEFT                            RIGHT
 SETTING         POS.     222222221111111111                       11111111112222222
                          765432109876543210987654321 012345678901234567890123456

 6  0 11  2    3.11296    EEDDCCCBAA99887665443322111 0FFFEEDDCCBAA98877665444332
 6  0 11  7    3.02596    EDDDCCBBAA99876655443322111 0FFFEEDDCCBBAA9877665544333
 6  0 11  8    3.00596    EDDDCCBBAA98876655443322111 0FFFEEDDCCBBAA9887665544333
 6  0 11  9    2.98897    EDDDCCBAAA98876655443322111 0FFFEEDDCCBBAA9887666544333
 6  0 11 12    2.94197    EDCCCCBAA998876655443322111 0FFFEEDDCCBBAA9887766544443
 6  0 12  1    2.86897    DDCCBBBA9998776655443322111 0FFFEEDDCCBBAA9987776555443
 6  0 12  6    2.79698    DCCCBBBA998877655444332210 00FFEEDDCCCBBA998877655544 4
 6  0 12 11    2.72598    DCBBBBAA998877655443322211 0 00FFEEEDDCCBBA9988776655554
 6  0 13  0    2.64499    CCBBBBA99887766554433222110 00FFEEEDDCCBBAA998877655554
 6  0 13  5    2.57300    CBBBAAA99887765554433221110 00FFFEEDDCCBBBA998877666555
 6  0 13 10    2.48400    CBBAAAA98877665544433221110 00FFFEEDDCCCBBAA99887666655
 6  0 13 15    2.41401    BBAAAA988877665544333221110 00FFFEEDDDCCBBAA99888766665
 6  0 14  4    2.33901    BAAA99988777665544332221110 00FFFEEEDDCCBBAA99988777666
 6  0 14  9    2.25902    AAA99998877665544433222 1110 00FFFEEEDDCCCBBAA9988777766
 6  0 14 14    2.17502    AA999988776665544333222 1110 00FFFEEEDDDCCBBAAA998877776
 6  0 15  3    2.09503    A99988877766654443332221110 00FFFEEEDDDCCCBAAA999888777
 6  0 15  8    2.02804    998988877766554443322211110 00FFFFEEEDDCCCBBAA999888787
 6  0 15 10    1.99204    998988877666554433322211110 00FFFFEEEDDDCCBBAAA99888787
 6  0 15 13    1.94303    998888777665554433322211110 00FFFFEEEDDDCCBBBAA99988887
 6  1  0  2    1.87703    988877776665554433322211100 000FFFEEEDDDCCBBBAAA9999888
 6  1  0  7    1.79803    888877766665544333222211100 000FFFEEEEDDDCCBBAAAA999888
 6  1  0 12    1.71902    887777766655543333222111100 000FFFFEEEDDDDCBBBAAA999998
 6  1  1  1    1.63402    877777666555443332222111100 000FFFFEEEEDDDCCBBBAAA99999
 6  1  1  6    1.56002    777766665554443332222111100 000FFFFEEEEDDDCCCBBBAAAA999
 6  1  1 11    1.48301    776666655554443322221111100 000FFFFFEEEEDDCCCBBBBAAAAA9
 6  1  2  0    1.40901    766656655544433322221111000 0000FFFFEEEEDDDCCCBBBAABAAA
 6  1  2  5    1.33401    666656555444433222211111000 0000FFFFFEEEEDDCCCCBBBABAAA
 6  1  2 10    1.25700    655555555444333222211111000 0000FFFFFEEEEDDDCCCBBBBBBBB
 6  1  2 15    1.17700    555555544443332222211111000 0000FFFFFEEEEEDDDCCCCBBBBBB
 6  1  3  4    1.10200    555545444433332222111110000 00000FFFFFEEEEDDDDCCCCBCBBB
 6  1  3  9    1.02399    544445444333332221111110000 00000FFFFFFEEEDDDDDCCCBCCCC
 6  1  3 11     .99199    544444443333332221111110000 00000FFFFFFEEEDDDDDDCCCCCCC
 6  1  3 14     .94699    444444443333322211111110000 00000FFFFFFFEEEDDDDDCCCCCCC
 6  1  4  3     .86699    443444433333222111111100000 000000FFFFFFFEEEDDDDDCCCCDC
 6  1  4  8     .78299    433434333332221111111100000 000000FFFFFFFFEEEDDDDDCDCDD
 6  1  4 13     .71599    333333333322221111111000000 0000000FFFFFFFEEEEDDDDDDDDD
 6  1  5  2     .63699    332333322222221111110000000 00000000FFFFFFEEEEEEEDDDDED
 6  1  5  7     .55800    322223322222211111100000000 000000000FFFFFFEEEEEEDDEEEE
 6  1  5 12     .48400    222222222222111111000000000 000000000FFFFFFEEEEEEEEEEEE
 6  1  6  1     .39600    222212222211111100000000000 000000000000FFFFFFEEEEEFEEE
 6  1  6  6     .30900    211212222111110000000000000 00000000000000FFFFFEEEEFEFF
 6  1  6 11     .23900    111112111111110000000000000 00000000000000FFFFFFFFEFFFF
 6  1  7  0     .14700    111111111100000000000000000 000000000000000000FFFFFFFFF
 6  1  7  5     .06600    110101100000000000000000000 000000000000000000000FF0F0F
 7  0  0  0     .00000    000000000000000000000000000 000000000000000000000000000
 7  0  0  1    -.01890    000000000000000F000C0000000 000000000000010000000000000
 7  0  0  5    -.08854    00000000000000FFFF0F0000000 000000001011110000000000000
 7  0  0 10    -.15519    F0F0F000000000FFFFFFF000000 000000011111110000000001010
 7  0  0 15    -.23082    FFFFF00FF00000FFFFFFFF00000 000000111111110000011001111
 7  0  1  4    -.31839    FFFFF00FFFFF0FFFFFFFFFF0000 000001111111111011111001111
 7  0  1  9    -.38309    EFFFFFFFFFFFFFFFFFFFFFFF000 000011111111111111111111111
 7  0  1 14    -.45675    EEEEEFFEFFFFFFFFFFFFFFFF000 000011111111111111112112222
 7  0  2  3    -.54237    EEEEEEEEEEFFFFEFFFFFFFFF000 000011111111121111222222222
 7  0  2  8    -.61407    DEEEEEEEEEEEFFEEFFFFFFFFF00 000111111111221122222222222
 7  0  2 13    -.69473    DDDEDEEEEEEEEFEEEFFFFFFFF00 000111111112221222222223233
 7  0  3  2    -.77740    DDDDDDEEEEEEEEEEEEEFFFFFF00 000111111222222222222233333
 7  0  3  7    -.84812    CDCDDDDDEEEEEEEEEEEFFFFFF00 000111111222222222223333343
```

```
                                                   PHASE SHIFTER STATES
 THUMBWHEEL         CRCTD                   LEFT                              RIGHT
 SWITCH             BEAM                                             111111111112222222
SETTING             POS.        222222221111111111
                                765432109876543210987654321 0123456789012345678901234567

  7  0  3 12      -.92883      CCCCDDDDDDDEEEEEEEEEFFFFF00 000111112222222223333333444
  7  0  4  0      -.99658      CCCCCDDDDDDDEEDEEEEEEFFFF00 000111122222232233333334444
  7  0  4  1     -1.01551      CCCCCDDDDDDDDEDEEEEEEFFFF00 000111122222232333333334444
  7  0  4  6     -1.07032      BBBCCCDDDDDDDEDEEEEEEFFFFF0 001111122222232333333344455
  7  0  4 11     -1.15903      BBBCCCCCCDDDDDDDEEEEEFFFFF0 001111122222333333344444455
  7  0  5  0     -1.23678      BBBBBCCCCCDDDDDDDEEEEEFFFF0 001111222223333333344444555
  7  0  5  5     -1.32053      BAABBCCCCCCCDDDDDDEEEEFFFF0 001111222223333334444444566
  7  0  5 10     -1.38933      AAAABBBBCCCCDDDDDDEEEEFFFF0 001111222233333334444555666
  7  0  5 15     -1.46811      AAAAABBBBCCCCDDDDDDEEEEFFF0 001112222333333444455556666
  7  0  6  4     -1.55389      A99AABBBBBCCCCCDDDDEEEEFFF0 001112222333344444555556677
  7  0  6  9     -1.62870      9999ABBBBBBCCCCCDDDDEEEFFF0 001112223333444444555555777
  7  0  6 14     -1.71251      99999ABABBBBCCCCCDDDEEEFFF0 001112223334444445555656777
  7  0  7  3     -1.78035      88899AAAABBBCCCCCDDDEEEFFF0 001112223334444445556666778
  7  0  7  8     -1.85820      88899AAAAABBBCCCCCDDDEEEFF0 001122233344444555666667788
  7  0  7 13     -1.92906      778899AAAABBBCBCCCDDDEEEFF0 001122233344454555666677889
  7  0  8  1     -1.99794      778889A9AAABBBBCCCDDDEEEFF0 001122233344455556667678889
  7  0  8  2     -2.01391      77888999AAABBBBCCCDDDEEEFF0 001122233344455556667778889
  7  0  8  7     -2.10077      777889999AAABBBBCCCDDEEEFF0 001122233444555566677778899
  7  0  8 12     -2.16368      667788999AAABBBBCCCDDDEEFF0 00112233344455556667778899A
  7  0  9  1     -2.24556      6667788999AAABBBCCCDDDEEFF0 0011223334445556667778899AA
  7  0  9  6     -2.32146      56677888999AABBBBCCCDDEEFF0 0011223344455556677788899AA
  7  0  9 11     -2.40438      5566778899 9AAAABBCCCDDEEFF0 001122334445566667778899AAB
  7  0 10  0     -2.48730      55566788899 9AAABBBCCDDEEFF0 001122334455566677888 9AABB
  7  0 10  5     -2.55425      45566778889 9AAAABBCCDDEEEF0 001222334455666677888 99AABB
  7  0 10 10     -2.62919      445567778899 9AAABBCCDDDEEF0 00122333445566677788999ABBC
  7  0 10 15     -2.70816      444566777889 9AAABBCCCDDEEF0 00122334445566677889 99AABCC
  7  0 11  4     -2.78512      3445567778899A9AABBCCDDEEF0 00122334455667677889 99ABBCC
  7  0 11  9     -2.87110      334556667888999AABBCCDDEEF0 0012233445566777889AAABBCD
  7  0 11 14     -2.94609      333445667788999AABBCCDDEEF0 00122334455667778899AABCCDD
  7  0 12  1     -2.99110      23344566678889 9AABBCCDDEEF0 0012233445566778889AAABCCDD
  7  0 12  3     -3.01209      23344566677889 9AABBCCDDEEFF 0112233445566778899AAABCCDD
  7  0 12  8     -3.09311      22334566677889 99AABBCDDEEFF 0112233455667778899AAABCDDE
  7  0 12 13     -3.17012      2223455567778999AABBCCDEEFF 011223445566777899 9ABBBCDEE
  7  0 13  2     -3.25016      1223445566778889AABBCCDEEFF 01122344556678889 9AABBCCDEE
  7  0 13  7     -3.32020      11223455667788899ABBCCDDEFF 0112334455677888 99AABBCDEEF
  7  0 13 12     -3.40827      1122344556677889 9AABCCDDEFF 0112334456677889 9AABBCCDEEF
  7  0 14  1     -3.47632      01122344566778899AABCCDDEFF 01123344566778899AABCCDEEFF
  7  0 14  6     -3.56040      0012234455667888 9AABBCDDEFF 01123345566788 89AABBCCDEEF0
  7  0 14 11     -3.63348      F0012344556677889 9ABBCDDEFF 0112334556778899AABBCCDEF00
  7  0 15  0     -3.71959      FF0123344556777899ABBCDDEFF 0112334556778999ABBCCDDEF01
  7  0 15  5     -3.79069      FF0112334556777899AABCCDEFF 0112344566778999ABBCDDEFF01
  7  0 15 10     -3.86881      EFF1123344566778 89AABCCDEFF 0112344566788 99AABCCDDEFF11
  7  0 15 15     -3.94996      EEF0122334556778 89AABCCDEFF 01123445667889 9ABBCDDEEF012
  7  1  0  3     -4.00306      EEF00123345567778 9AABCCDEEF 012234456678999ABBCDDEF0012
  7  1  0  4     -4.02009      EEF00122345567778 9AABCCDEEF 012234456678999ABBCDEEF0012
  7  1  0  9     -4.09625      DEE00122344566778 99ABCCDEEF 0122344567789 9AABCCDEEF0022
  7  1  0 14     -4.17643      DDEF012234455667899ABBCDEEF 012234556778 9AABBCCDEEF0123
  7  1  1  3     -4.25260      CDEF0112234556678 89ABBCDEEF 012234556788 9AABBCDEEFF0123
  7  1  1  8     -4.33280      CDEEF01123445667889ABBCDEEF 0122345567889AABCCDEFF01223
  7  1  1 13     -4.41201      CCDEF0112334566778 9AABCDEEF 0122345667899AABCDDEFF01234
  7  1  2  2     -4.47518      BCDEE001233455677 89AABCDDEF 012334566789 9ABBCDDEF002234
  7  1  2  7     -4.56244      BCCEE0012234456678 99ABCDDEF 01233456778 9AABCCDEEF002244
  7  1  2 12     -4.64268      BBCDEF011234455678 99ABCDDEF 01233456778 9ABBCCDEFF012345
  7  1  3  1     -4.72092      ABCDEF00122345567889ABCDDEF 01233456788 9ABBCDEEF0012345
  7  1  3  6     -4.79217      ABBDDFF011234556788 9ABCCDEF 01234456788 9ABBCDEFF0113355
  7  1  3 11     -4.87143      AABCDEF0012345567789ABCCDEF 0123445678 99ABBCDEF00123456
  7  1  4  0     -4.95272      9ABCDEFF012334566789ABCCDEF 01234456789AABCDDEF01123456
 THUMBWHEEL      CRCTD                       PHASE SHIFTER STATES
  SWITCH         BEAM                LEFT                                  RIGHT
 SETTING         POS.     222222221111111111                    11111111112222222
                          765432109876543210987654321 012345678901234567890123456

  7  1  4  3    -4.99689  9AACDEFF012334556789ABBCDEF 01234556789ABBCDDEF01123466
  7  1  4  4    -5.01693  9AACDEFF012234556789ABBCDEF 01234556789ABBCDEEF01123466
  7  1  4  5    -5.03101  9AACCEFF012234556789ABBCDEF 01234556789ABBCDEEF01124466
  7  1  4 10    -5.11332  99ABCEEF011234456789ABBCDEF 01234556789ABCCDEFF01224567
  7  1  4 15    -5.18460  89ABCDEFF01234456789AABCDEF 01234566789ABCCDEF011234567
  7  1  5  4    -5.25890  899BBDEEF012344567889ABCDEF 01234567889ABCCDEF012235577
  7  1  5  9    -5.32117  789ABDDEF012334567889ABCDEF 01234567889ABCDDEF012335678
  7  1  5 14    -5.41859  789ABCDEF011234566789ABCDEF 0123456789AABCDEFF012345678
  7  1  6  3    -5.50397  788AACDEF001234456789ABCDEF 0123456789ABCCDEF0012346688
  7  1  6  8    -5.58133  678AACDEEF01233456789ABCDEF 0123456789ABCDDEF0122346689
  7  1  6 13    -5.66172  6789ABCDEF01223456789ABCDEF 0123456789ABCDEEF0123456789
  7  1  7  2    -5.75619  6789ABCDDEF0123456789ABCDEF 0123456789ABCDEF01233456789
  7  1  7  7    -5.82353  56799BCCDEF0123456789ABCDEF 0123456789ABCDEF0123445779A
  8  0  0  0    -5.86776  56789ABCDEF0123456789ABCDEF 0123456789ABCDEF0123456789A
  8  0  0  8    -6.00278  56788ABCDEF0122345678ABCDEF 012345689ABCDEEF0123456889A
  8  0  4  9    -7.00098  01245688ABCDEF01345679ABCDF 01345679ABCDF012345688ABCEF
  8  0  8  8    -7.99873  CDE01245689ACDEF1235689ACDF 0134678ABDEF1234678ABCEF023
  8  0  8  9    -8.01284  CCE01245689ACDEF1235689ACDF 0134678ABDEF1234678ABCEF024
  8  0 12  9    -9.00107  78ABDF0235689BCDF023578ABDE 0235689BDE0134578ABDE013568
  8  1  0  9   -10.00097  24589BDE023578ABDF024679BCE 024579ACE0135689BDE023578BC
  8  1  4  8   -10.99949  EF14589BDF124679BDF13568ACE 02468ABDF13579ACEF13578BCF1
  8  1  4  9   -11.01782  EF14589BDF024679BDF13568ACE 02468ABDF13579ACE013578BCF1
  9  0  0  0   -11.79822  ACE02468ACE02468ACE02468ACE 02468ACE02468ACE02468ACE024
  9  0  0 13   -12.00258  9BD01467ACE024579BDF1368ACE 02468ADF13579BCE02469ACF035
  9  0  4 12   -13.00018  579CD02469BDF1358ACE03579BE 02579BD02468BDF1357ACE03479
  9  0  8 11   -14.00320  0258ACF1368ADF1368ADF1469BE 0257ACF1368ADF1368ADF1468BE
  9  0 12 10   -15.00450  CE1369BE0358ADF1469BE0368BD 0358AD0257ACF1368BD0257ADF2
  9  1  0  8   -16.00096  7AD0258AD0258ADF257AD0258AD 03683E0369BE1368BE0368BE036
  9  1  4  6   -17.00303  368CE247AD0258BD0369CF147AD 0369CF147AD0358BE0369CE248A
 10  0  0  0   -17.86037  F258BE147AD0369CF258BE147AD 0369CF258BE147AD0369CF258BE
 10  0  0  8   -18.00153  F258AE147AD0368BE147AE147AD 0369CF269CF258AD0369CF268BE
 10  0  4  7   -19.00850  AD047AE147AD0469D0369D0369D 037AD037AD037AC0369CF269C03
 10  0  8  3   -20.00392  69C037AD147BE148BE258CF269D 037AE148BE258CF259CF369D047
 10  0 11 15   -21.00249  258CF37AD158CF269D047BE259D 037BE259C037AE148BF369D148B
 10  0 15 12   -22.00970  D148C047BE259D047BF26AD159C 047BF36AE159C037BE259C048CF
 10  1  3  8   -23.00528  9C058D048BF37BE269D159D048C 048C037BF37AE259D158C038B04
 10  1  7  1   -23.99643  59D159D158C048C048C048C048C 048C048C048C048C048BF37BF37
 10  1  7  2   -24.01614  59D159D148C048C048C048C048C 048C048C048C048C048CF37BF37
 11  0  0  0   -24.13771  48C048C048C048C048C048C048C 048C048C048C048C048C048C048
 11  0  3  2   -24.99246  159D15AE26AE26AE26AF37BF38C 048D159D16AE26AE26AE26BF37B
 11  0  3  3   -25.00785  158D15AE26AE26AE26AF37BF38C 048D159D16AE26AE26AE26BF38B
 11  0  6 13   -26.00836  D159D27AF37B048C159D26AF37C 049D16AE37BF48C059D169E37BF
 11  0 10  7   -26.99625  8C16AF38C059E26AF38C159E27C 049E27BF48D16AE27B048D16AF4
 11  0 10  8   -27.01416  8C16AF37C059E26AF38C159E27C 049E27BF48D16AE27B049D16AF4
 11  0 14  1   -28.00621  49D26B049E27B049D26B049D27B 059E37C05AE37C059E27C05AE37
 11  1  1  9   -28.99333  059E38D16B049E27C05AF38D26B 05AE38D16B049E27C05AF38D27B
 11  1  1 10   -29.01047  059E38D16B049E27C05AE38D26B 05AE38D26B049E27C05AF38D27B
 11  1  5  2   -30.00308  C15B05AE38D27C05AF49D27C16B 05AF49E37C16B049E38D26B05BF
 12  0  0  0   -30.74140  9E38D27C16B05AF49E38D27C16B 05AF49E38D27C16B05AF49E38D2
 12  0  0 15   -31.01033  8D27C27B06B05AE38D27C17C16B 05AF49F49E38D26B05A059E49E3
 12  0  4  7   -32.01721  49E49E49E38D28C17C16B16B05B 05B05AF5AF49F48E38D27C27C27
 12  0  7 12   -33.00445  15B06B16B06B06A05A05A05A05B 05B06B06B06B06A05A05AF5A05B
 12  0 11  3   -34.01592  C27D28E38E39E49E39E49F4AF5B 05B16C17C27D27C27D28D28E39E
 12  0 14  7   -34.99527  9E49F5B06B16C27C28D38E49F5A 06B17C28D38E49E4AF5A05B17C2
 12  0 14  8   -35.01967  9E49F5B06B16C17C28D38E49F5A 06B17C28D38E49F4AF5A05B17C2
 12  1  1 12   -35.99825  5A06C28D39F4A05B06C27D39F4A 06C17D39E4A05B06C17D38E4A06
 12  1  1 13   -36.02173  5A06C28D39E4A05B06C27D39F4A 06C17D39E4A05B06C27D38E4A06
 THUMBWHEEL         CRCTD                       PHASE SHIFTER STATES
 SWITCH             BEAM                  LEFT                            RIGHT
SETTING             POS.      222222221111111111                    11111111112222222
                              765432109876543210987654321 012345678901234567890123456

12  1  5  0  -36.99575   17D39F5B06C28E39F5B16C28E4A 06C28E4AF5B17D28E4A05B17D39
12  1  5  1  -37.01328   17C39F5B06C28E39F5B16C28E4A 06C28E4AF5B17D28E4A05B17D49
13  0  0  0  -37.83552   E4A06C28E4A06C28E4A06C28E4A 06C28E4A06C28E4A06C28E4A06C
13  0  0  8  -38.00577   E4A05C28E4A06C17D39F5C28E4A 06C28E4B17D39F4A06C28E4B06C
13  0  3 11  -39.00320   A06D39F5B17E4A06C28E5B17D4A 06C39F5B28E4A06C29F5B17D3A0
13  0  6 13  -40.01349   7D39F6D29F5B28E4B17D4A07D3A 06D3906C39F5C28E5B17E3A17D3
13  0  9 13  -40.99502   3906D3A06D3906C3906C3906D3A 06D3A07D4A07D4A07D3A06D3A07
13  0  9 14  -41.01353   3906C3A06D3906C3906C3906D3A 06D3A07D4A07D4A07D3A06D4A07
13  0 12 15  -42.00292   F6C3A17D4B17E4B18E5B28F6C39 07D4A18E5B28F5C29F5C39F6D4A
13  0 15 14  -43.00309   C3907E4B18F5C3906D4A18E5C39 07D4B28F6C3A07D4B18F5C2907D
13  1  2 13  -43.99813   9F6D4B28F6D4A17E5C3907E5B29 07E5B2907D4B29F6C3A18E5C3A1
13  1  2 14  -44.02454   9F6D4B28F6D3A17E5C3907E5B29 07E5B2907D4B29F6D3A18E5C3A1
13  1  5 12  -45.00613   5C3A18F6D4B28F6D4B18F6D4B29 07E5C3A18F5C3A18E5C3A18F6D4
13  1  7  7  -45.63187   3A19F7E4B2907E5C3A18F6D4B29 07E5C3A18F6D4B2907E5C2917F6
13  1  7  8  -45.65189   3A18F7E4B2907E5C3A18F6D4B29 07E5C3A18F6D4B2907E5C2918F6
13  1  7  9  -45.67479   3A18F7D4B2907E5C3A18F6D4B29 07E5C3A18F6D4B2907E5C3918F6
```

```
CORRECTED BEAM ANGLES FOR SCAN PROGRAM 1
DATE: 07/01/84
FREQUENCY= 5090 MHZ

                                                                          PAGE 1
 THUMBWHEEL       CRCTD                     PHASE SHIFTER STATES
 SWITCH           BEAM              LEFT                               RIGHT
SETTING           POS.     222222221111111111                   11111111112222222
                           765432109876543210987654321 012345678901234567890123456

 0  0  0  0     45.34990   D6F81A3C5E7092B4D6F81A3C5E7 092B4D6F81A3C5E7092B4D6F81A
 0  0  0  1     45.32317   D6F81A3C5E7092B3D6F81A3C5E7 092B4D6F81A3D5E7092B4D6F81A
 0  0  0  2     45.29926   D6F81A3C5E7092B3D5F81A3C5E7 092B4D6F81B3D5E7092B4D6F81A
 0  0  0  3     45.27115   D6F81A3C5E7092A3D5F81A3C5E7 092B4D6F81B3D6E7092B4D6F81A
 0  0  1  0     44.99915   C5E70A3B4D7092A3C5E7093C5E7 092B4D7092B4D6E7093C5D6092B
 0  0  3 14     44.00406   92B4D7092B4D7092B4D6092B4E7 092C5E70A3C5E7093C5E7093C5E
 0  0  3 15     43.97790   92B4D7092B4D7082B4D6092B4E7 092C5E70A3C5E8093C5E7093C5E
 0  0  6 13     43.00130   6F81A4E6092B5E70A3C5F81B4D7 093C5F81B4D6092B5E70A2C6F81
 0  0  6 14     42.97690   6F81A4E6092B5E7093C5F81B4D7 093C5F81B4D7092B5E70A2C6F81
 0  0  9 13     41.99504   2B5E81B4D7093C5F82B4E71A4D7 093C6F92C5E81B4D7093C5F82B5
 0  0 12 15     40.99316   E81B5F81B5E71A4D70A3D60A3D6 0A3D60A3D6093C6F92B5F81B5F8
 0  1  0  0     39.99139   B4E81C5F82C5F92C5F92C6F93D6 0A3D71A4E71B4E71B4E81B4F82C
 0  1  3  2     39.00102   71B5E93C6093D70A4E71B5F92C6 0A4E71B5F92C6093D70A4D72B5F
 0  1  3  3     38.98056   71B5E92C6093D70A4E71B5F92C6 0A4E71B5F92C6093D70A4E72B5F
 0  1  6  4     38.00644   4E72B60A4D71B5F82C60A4E82C6 0A4E82C60A4E81B5F93C60A5E92
 0  1  6  5     37.98121   4E72B60A4D71B5E82C60A4E82C6 0A4E82C60A4E82B5F93C60A5E92
 1  0  0  0     37.57371   2C60A4E82C60A4E82C60A4E82C6 0A4E82C60A4E82C60A4E82C60A4
 1  0  1 14     37.00299   0A4E83D61B5F93D71B5F93D72C6 0A4E93D71B5F93D71B5FA3D82C6
 1  0  1 15     36.98193   0A4E83D60B5F93D71B5F93D72C6 0A4E93D71B5F93D71B50A3D82C6
 1  0  5  2     35.99410   D71B50A4E82D71B5F94E82D71B6 0A5F93E82C71B5F93E82C60B5F9
 1  0  8  6     35.00408   93D82D71B60A5F93E83D72C61B6 0A5FA4E93D82D71B60A5F93E83D
 1  0  8  7     34.98350   93D82D71B60A5F93E82D72C61B6 0A5FA4E93E82D71B60A5F93E83D
 1  0 11 12     33.99864   5F94FA4E93E83D72C71C61B60B6 0A50A5FA4F94E93D82D72C61C71
 1  0 15  2     33.00778   1B61B71B61B61B50B50B50B50B5 0B50B50B50B50B5FA5FA5F95FA5
 1  0 15  3     32.99001   1B61B61B61B61B50B50B50B50B5 0B50B50B50B50B5FA5FA5FA5FA5
 1  1  2 10     32.00269   D72D83E94E94E94E94F94FA5FA5 0B61B61C71C72C72C72C72D83E9
 1  1  2 11     31.98276   D72D83E93E94E94E94F94FA5FA5 0B61B61C71C72C72C72D72D83E9
 1  1  6  1     30.99892   94FA40B61C61C72D72D83E94FA5 0B61C72D83E93E94FA4FA50C61C
 2  0  0  0     30.54077   72D83E94FA50B61C72D83E94FA5 0B61C72D83E94FA50B61C72D83E
 2  0  1 15     29.99556   50B61D82D94FA50B61C72D83FA5 0B61D83E94FA50B61C73E83FA50
 2  0  5  7     29.00338   1C73E950B61C83E94FB61C83E95 0B72D84FA51C72D84FA50B72D94
 2  0  5  8     28.98412   1C73E95FB61C83E94FB61C83E95 0B72D84FA51C72D84FA51B72D94
 2  0  9  0     28.00034   D83FA62D83FA51C73E950B72E95 0B72E950B72D94FB61D83EA61D8
 2  0  9  1     27.98237   D83FA61D83FA51C73E950B72E95 0B72E950B72D94FB61D83FA61D8
 2  0 12 10     27.00336   940B73EA51C83FA51C83FA62D94 0C73EA61D84FB61D84FB62D950C
 2  0 12 11     26.98776   94FB73EA51C83FA51C83FA62D94 0C73EA61D84FB61D84FB62D951C
 2  1  0  4     26.00555   50C83FB62EA51D83FB72EA51D84 0C83FB62E951D83FB62EA51D840
 2  1  0  5     25.99781   40C83FB62EA51D83FB72EA51D84 0C83FB62E951D83FB62EA51D840
 2  1  3 15     25.00239   0C840C83FB73FA62D951D950C84 0C840B73FB73EA61D951D840C84
 2  1  4  0     24.98155   0C840C83FB73EA62D951D950C84 0C840B73FB73EA62D951D840C84
 2  1  7  9     24.00171   C840C940C840C840C840C840C84 0C840C840C840C840C840C740C8
 3  0  0  0     23.98648   C840C840C840C840C840C840C84 0C840C840C840C840C840C840C8
 3  0  3 11     22.99484   840D951D951EA62EA62EB73FB84 0C851D952EA62EA62FB73FB730C
 3  0  7  7     21.99838   40C952EA62FB740C851D962EB74 0C952EA73FB840C951EA62EB740
 3  0 11  4     20.99074   FC851EB730C952DA63FC851EA74 0C962FB841DA63EB740D952FB84
 3  0 15  0     20.00060   B741EB740D963FB851EB741DA73 0D963FC952FB851DA730C952FC9
 3  0 15  1     19.98262   B741EB730D963FB851EB741DA73 0D963FC952FB851DA730D952FC9
 3  1  2 14     18.99176   730DA740DA730D9630D9630D963 0DA730DA730DA730D9630C9630D
 3  1  6 11     18.00124   2FC9640DA741EB741EB852FC963 0DA741EB852FC952FC9630CA741
 3  1  6 12     17.98556   2FC9630DA741EB741EB852FC963 0DA741EB852FC952FC9630DA741
 4  0  0  0     17.75159   1EB852FC9630DA741EB852FC963 0DA741EB852FC9630DA741EB852
 4  0  2 14     17.00822   EB8620DA741EB852FDA741EB863 0DA852FC9631EB852FC9630EA85
 4  0  2 15     16.98959   EB8620DA741EB852FCA741EB863 0DA852FC9641EB852FC9630EA85
```

```
                                               PHASE SHIFTER STATES
 THUMBWHEEL        CRCTD                                                           RIGHT
  SWITCH           BEAM                      LEFT                        11111111112222222
 SETTING           POS.       222222221111111111
                              765432109876543210987654321 012345678901234567890123456

  4  0  6 13     15.99145     A741ECA641EB9630EB8530DB853 0DB8530DB8520DA752FCA642FC9
  4  0 10 11     15.00836     520DB9631EB9641EC9742FCA753 0DB9641EC9742FCA752FDA7530E
  4  0 10 12     14.99295     520DB8631EB9641EC9742FCA753 0DB9641EC9742FCA752FDA8530E
  4  0 14 11     13.99815     0EB97530EB9641FCA7520EC9752 0EB97420DB9641FCA7520DB9752
  4  1  2 10     13.00689     C97531FDB8641FDA8641FDB9642 0ECA7531FCA8631FCA8531FDB97
  4  1  2 11     12.98955     C97531FDA8641FDA8641FDB9642 0ECA7531FCA8631FCA8631FDB97
  4  1  6  9     12.00094     7532FEC97531FDA86420ECA8642 0ECA86420ECA8631FDB97421EDB
  4  1  6 10     11.98671     7531FEC97531FDA86420ECA8642 0ECA86420ECA8631FDB97421FDB
  5  0  0  0     11.72769     6420ECA86420ECA86420ECA8642 0ECA86420ECA86420ECA86420EC
  5  0  2 14     11.00407     31FEBA86420ECA86431FDB97542 0ECB97531FDCA86420ECA86521F
  5  0  2 15     10.98591     31FEBA86420ECA86421FDB97542 0ECB97531FECA86420ECA86521F
  5  0  6 14      9.99442     FDB976521FDBA86421FDCA87532 0EDB986431FECA86531FEBA9753
  5  0 10 14      9.00571     A875421FDCA976421FECA976432 0EDCA976421FECA976431FECB98
  5  0 10 15      8.99164     A865421FDCA976421FECA976432 0EDCA976421FECA976431FECBA8
  5  0 14 15      7.99169     54210FDCA9765310FDCB9875431 0FDCB98754310FDBA9764310FEC
  5  1  3  0      6.99442     0FEDCBA8765321FEDCA98765321 0FEDBA98764321FEDBA98654321
  5  1  6 15      5.99896     CBA987654320FEDCBA987654321 0FEDCBA9876543210EDCBA98765
  6  0  0  0      5.83306     BA9876543210FEDCBA987654321 0FEDCBA9876543210FEDCBA9876
  6  0  0  3      5.77739     BA9876543210FECBB9987654321 0FEDCBA9877554210FEDCBA9876
  6  0  0  8      5.69887     BA9866543210FECBA9876654321 0FEDCBAA987654210FEDCBAA876
  6  0  0 13      5.63326     A98866533210FECBA9876554321 0FEDCBBA987654210FEDDBAA887
  6  0  1  2      5.55375     A9876653211FFECBA9876544321 0FEDCCBA987654211FFEDBAA987
  6  0  1  7      5.46627     A9876543210FEDCBA9876544321 0FEDCCBA9876543210FEDCBA987
  6  0  1 12      5.40763     99765543210FEDCBA9876543321 0FEDDCBA9876543210FEDCBBA97
  6  0  2  1      5.32612     98765442100FEDCBA9876543321 0FEDDCBA98765432100FECCBA98
  6  0  2  6      5.24661     9876543210FFEDBAA9876543221 0FEEDCBA98766532110FEDCBA98
  6  0  2 11      5.17306     8766543210FEDDBAA9876543221 0FEEDCBA98766533210FEDCBAA9
  6  0  3  0      5.08856     8765443210FEDCBA98876543221 0FEEDCBA98876543210FEDCCBA9
  6  0  3  5      5.00805     8755433100FEDCBA98776543221 0FEEDCBA998765432100FDDCBB9
  6  0  3  6      4.99314     8755432100FEDCBA98776543221 0FEEDCBA998765432100FEDCBB9
  6  0  3 10      4.93847     765543210FFEDCBA98766543221 0FEEDCBAA98765432110FEDCBBA
  6  0  3 15      4.85299     765433210FEDDCAA98766543221 0FEEDCBAA98766433210FEDDCBA
  6  0  4  4      4.78639     754433210FEDCCAA98765543211 0FFEDCBBA98766443210FEDDCCB
  6  0  4  9      4.70886     654432200FE CBA998765543211 0FFEDCBBA987765432100EEDCCB
  6  0  4 14      4.63530     65432210FFEDCBA998765443211 0FFEDCCBA987765432110FEEDCB
  6  0  5  3      4.54783     64432210FEDDCBA987765443211 0FFEDCCBA998765433210FEEDCC
  6  0  5  8      4.47627     5433211FFEDCCBA987765443211 0FFEDCCBA998765443211FFEDDC
  6  0  5 13      4.39972     5432210FFEDCBBA987665433211 0FFEDDCBAA987655432110FEEDC
  6  0  6  2      4.32021     5322110FEEDCBB9987665433211 0FFEDDCBAA987755432210FFEED
  6  0  6  7      4.24068     4322110FEDDCBA9887655433211 0FFEDDCBBA988765433210FFEED
  6  0  6 12      4.16216     4321000EEDCCBA9887655433211 0FFEDDCBBA98876544322000FED
  6  0  7  1      4.08066     421100FEEDCBBA9877655433211 0FFEDDCBBA998765543221 00FFE
  6  0  7  6      4.01405     321100FEDDCBAA9877654432211 0FFEEDCCBA99876654332100FFE
  6  0  7  7      3.99616     321100FEDCCBAA9877654432211 0FFEEDCCBA99876654432100FFE
  6  0  7 11      3.93155     32100FFEDCCBAA8876654432211 0FFEEDCCBAA98866544321100FE
  6  0  8  0      3.85402     21100FFDDCBBA98876654432211 0FFEEDCCBAA98876554331100FF
  6  0  8  5      3.77251     2100FFEDDCBAA98776654432211 0FFEEDCCBAA998766543321100F
  6  0  8 10      3.70193     1000FEEDCCBAA98776554432211 0FFEEDCCBBA998766544321000
  6  0  8 15      3.62341     10FFFEEDCBBA998776554332211 0FFEEDDCBBA998776554321110
  6  0  9  4      3.53991     10FFEEDCCBAA998766554332211 0FFEEDDCBBAA98776654432110
  6  0  9  9      3.47033     0FFEEEDCCBAA988766544332211 0FFEEDDCCBAA98876654432211
  6  0  9 14      3.38485     0FFEDDDCBBA998776654433 2211 0FFEEDDCCBAA99877655433 3211
  6  0 10  3      3.31129     0FEEDDCCBBA9987665544332111 0FFFEDDCCBBAA98776554433221
  6  0 10  8      3.24569     FEEEDDCBBAA9987665544322111 0FFFEEDCCBBAA98776655433222
  6  0 10 13      3.16417     FEEDDCCBBA99887665543322111 0FFFEEDDCBBAA98877655443322
  6  0 11  2      3.09459     EEDDCCCBAA99887665443322111 0FFFEEDDCCBAA98877665444332
 THUMBWHEEL        CRCTD                       PHASE SHIFTER STATES
  SWITCH           BEAM             LEFT                                  RIGHT
 SETTING           POS.      222222221111111111                     11111111112222222
                             765432109876543210987654321 012345678901234567890123456

  6  0 11  8     2.98823     EDDDCCBBAA9887665544332211l 0FFFEEDDCCBBAA9887665544333
  6  0 11 12     2.92462     EDCCCCBAA998876655443322111 0FFFEEDDCCBBAA9887766544443
  6  0 12  1     2.85205     DDCCBBBA9998776655443322111 0FFFEEDDCCBBAA9987776555443
  6  0 12  6     2.78048     DCCCBBBA9988776554443322110 00FFEEDDCCCBBA9988776555444
  6  0 12 11     2.70990     DCBBBEAA9988776554433222110 00FFEEEDDCCBBA9988776655554
  6  0 13  0     2.62939     CCBBBBA99887766554433222110 00FFEEEDDCCBBAA998877655554
  6  0 13  5     2.55782     CBBBAAA99887765554433221110 00FFFEEDDCCBBBA998877666555
  6  0 13 10     2.46935     CBBAAAA98877665544433221110 00FFFEEDDCCCBBAA99887666655
  6  0 13 15     2.39977     BBAAAA988877665544333221110 00FFFEEDDDCCBBAA99888766665
  6  0 14  4     2.32522     BAAA99988777665544332221110 00FFFEEEDDCCBBAA99988777666
  6  0 14  9     2.24570     AAA99998877665544433222111 0 00FFFEEEDDCCCBBAA9988777766
  6  0 14 14     2.16219     AA999988776665544333222111 0 00FFFEEEDDDCCBBAAA998877776
  6  0 15  3     2.08268     A9998887776665444333222111 0 00FFFEEEDDDCCCBAAA999888777
  6  0 15  8     2.01608     998988877766554443322211110 00FFFFEEEDDCCCBBAA999888787
  6  0 15  9     1.99819     998988877766554433322211110 00FFFFEEEDDDCCBBAA999888787
  6  0 15 13     1.93157     998888777665554433322211110 00FFFFEEEDDDCCBBBAA99988887
  6  1  0  2     1.86596     988877776665554433322211100 000FFFEEEDDDCCBBBAAA9999888
  6  1  0  7     1.78743     888877766665544333222211100 000FFFEEEEDDDCCBBAAAA999888
  6  1  0 12     1.70889     887777766655543333222111100 000FFFFEEEDDDDCBBBAAA999998
  6  1  1  1     1.62439     877777666555443332222111100 000FFFFEEEEDDDCCBBBAAA99999
  6  1  1  6     1.55082     777766665554443332222111100 000FFFFEEEEDDDCCCBBBAAAA999
  6  1  1 11     1.47427     776666655554443322221111100 000FFFFFEEEEDDCCCBBBBAAAAA9
  6  1  2  0     1.40070     766656665554443332222111100 0 0000FFFFEEEEDDDCCCBBBAABAAA
  6  1  2  5     1.32615     666656555444433222211111000 0000FFFFFEEEEDDCCCCBBBABAAA
  6  1  2 10     1.24959     655555555444333222211111000 0000FFFFFEEEEDDDCCCBBBBBBBB
  6  1  2 15     1.17006     555555544443332222211111000 0000FFFFFEEEEEDDDCCCCBBBBBB
  6  1  3  4     1.09550     555545444433332222111110000 00000FFFFFEEEEDDDDCCCCBCBBB
  6  1  3  9     1.01795     544445444333332221111110000 00000FFFFFFEEEDDDDDCCCBCCCC
  6  1  3 10     1.00304     544444444333332221111110000 00000FFFFFFEEEDDDDDCCCCCCCC
  6  1  3 11      .98614     544444443333332221111110000 00000FFFFFFEEEDDDDDDCCCCCCC
  6  1  3 14      .94141     444444443333322211111110000 00000FFFFFFFEEEDDDDDCCCCCCC
  6  1  4  3      .86188     443444433333222111111100000 000000FFFFFFFEEEDDDDDCCCCDC
  6  1  4  8      .77838     433434333332221111111100000 000000FFFFFFFFEEEDDDDDCDCDD
  6  1  4 13      .71177     333333333322221111111000000 0000000FFFFFFFEEEEDDDDDDDDD
  6  1  5  2      .63324     332333322222221111110000000 00000000FFFFFFEEEEEEEDDDDED
  6  1  5  7      .55471     322223322222221111100000000 000000000FFFFFFEEEEEEEDDEEEE
  6  1  5 12      .48114     222222222222211111100000000 0000000000FFFFFFEEEEEEEEEEE
  6  1  6  1      .39366     222212222211111100000000000 00000000000FFFFFFEEEEEEFEEE
  6  1  6  6      .30718     211212222111110000000000000 00000000000000FFFFFEEEEFEFF
  6  1  6 11      .23759     111112111111110000000000000 00000000000000FFFFFFFEFFFFF
  6  1  7  0      .14613     111111111100000000000000000 000000000000000000FFFFFFFFF
  6  1  7  5      .06561     110101100000000000000000000 000000000000000000000FF0F0F
  7  0  0  0      .00000     000000000000000000000000000 000000000000000000000000000
  7  0  0  1    -.01879      000000000000000F00000000000 000000000000010000000000000
  7  0  0  5    -.08802      00000000000000FFFF0F0000000 000000001011110000000000000
  7  0  0 10    -.15428      F0F0F000000000FFFFFFF000000 000000011111110000000001010
  7  0  0 15    -.22946      FFFFF00FF00000FFFFFFFF00000 000000111111110000011001111
  7  0  1  4    -.31652      FFFFF00FFFFF0FFFFFFFFFF0000 000001111111110111111001111
  7  0  1  9    -.38083      EFFFFFFFFFFFFFFFFFFFFFFF000 000011111111111111111111111
  7  0  1 14    -.45406      EEEEEFFEFFFFFFFFFFFFFFFF000 000011111111111111112112222
  7  0  2  3    -.53917      EEEEEEEEEEFFFFEFFFFFFFFF000 000011111111121111222222222
  7  0  2  8    -.61045      DEEEEEEEEEEEFFEEFFFFFFFFF00 000111111111221122222222222
  7  0  2 13    -.69063      DDDEDEEEEEEEEFEEEFFFFFFFF00 000111111112221222222223233
  7  0  3  2    -.77282      DDDDDDEEEEEEEEEEEEFFFFFF00  000111111222222222222233333
  7  0  3  7    -.84312      CDCDDDDDDEEEEEEEEEEFFFFFF00 000111111222222222233333343
  7  0  3 12    -.92335      CCCCDDDDDDDEEEEEEEEEFFFFF00 000111112222222222333333444
  7  0  4  1   -1.00953      CCCCCDDDDDDDDEDEEEEEEFFFF00 000111122222232333333334444
 THUMBWHEEL       CRCTD                      PHASE SHIFTER STATES
 SWITCH           BEAM             LEFT                                  RIGHT
SETTING           POS.    222222221111111111                     11111111112222222
                          765432109876543210987654321 012345678901234567890123456

  7  0  4  6    -1.06401  BBBCCCDDDDDDDEDEEEEEEEFFFFF0 001111122222232333333344455
  7  0  4 11    -1.15220  BBBCCCCCCDDDDDDDDEEEEEFFFFF0 001111122222333333334444455
  7  0  5  0    -1.22949  BBBBBCCCCCDDDDDDDEEEEEFFFF0 001111222223333333444445555
  7  0  5  5    -1.31275  BAABBCCCCCCCDDDDDDEEEEEFFFF0 001111222233333334444445566
  7  0  5 10    -1.38114  AAAABBBBCCCCDDDDDDEEEEEFFFF0 001111222233333334444555566
  7  0  5 15    -1.45946  AAAAABBBBCCCCDDDDDDEEEEEFFF0 001112222333333444455556666
  7  0  6  4    -1.54473  A99AABBBBBCCCCCDDDDEEEEEFFF0 001112222333344444555556677
  7  0  6  9    -1.61910  9999ABBBBBBCCCCCDDDDEEEEFFF0 001112223333444444555555677
  7  0  6 14    -1.70241  99999ABABBBBCCCCCDDDEEEFFF0 001112223334444455555656777
  7  0  7  3    -1.76986  88899AAAABBBCCCCCDDDEEEFFF0 001112223334444455566666778
  7  0  7  8    -1.84724  88899AAAAABBBCCCCCDDDEEEFF0 001122233344444555666667788
  7  0  7 13    -1.91768  778899AAAABBBCBCCCDDDEEEFF0 001122233344454555666677889
  7  0  8  2    -2.00204  77888999AAABBBBCCCDDDEEEFF0 001122233344455555666777889
  7  0  8  7    -2.08838  777889999AAABBBBCCCDDEEEFF0 001122233444555556677778899
  7  0  8 12    -2.15092  667788999AAABBBBCCCDDDEEFF0 001122333444555556677778899A
  7  0  9  1    -2.23232  6667788999AAABBBCCCDDDEEFF0 001122333444555666777788899AA
  7  0  9  6    -2.30777  56677888999AABBBBCCCDDEEFF0 001122334445555667778889 9AA
  7  0  9 11    -2.39020  55667788999AAAABBCCCDDEEFF0 001122334445566667778899AAB
  7  0 10  0    -2.47263  555667888999AAABBBCCDDEEFF0 0011223344555666777888 9AABB
  7  0 10  5    -2.53918  455667788899AAAABBCCDDEEEF0 001222334455666677888 99AABB
  7  0 10 10    -2.61369  4455677788999AAABBCCDDDEEF0 001223334455666777788999ABBC
  7  0 10 15    -2.69218  4445667778699AAABBCCCDDEEF0 001223344455666778899 9AABCC
  7  0 11  4    -2.76869  34455677788?9A9AABBCCDDEEF0 00122334455667677889999ABBCC
  7  0 11  9    -2.85416  334556667888999AABBCCDDEEF0 0012233445566777788 9AAABBCD
  7  0 11 14    -2.92871  333445667788999AABBCCDDEEF0 00122334455667778899AABCCDD
  7  0 12  3    -2.99432  233445666778899AABBCCDDEEFF 01122334455667788 99AAABCCDD
  7  0 12  4    -3.01321  233445666778899 9ABBCCDDEEFF 01122334455677788 99AAABCCDD
  7  0 12  8    -3.07486  223345666778899 9AABBCDDEEFF 01122334556677788 99AAABCDDE
  7  0 12 13    -3.15142  222345556777899 9AABBCCDEEFF 0112234455667778999ABBBCDEE
  7  0 13  2    -3.23099  12234455667788899AABBCCDEEFF 011223445566788899AABBCCDEE
  7  0 13  7    -3.30061  11223455667788899ABBCCDDEFF 01123344556778889 9AABBCDEEF
  7  0 13 12    -3.38815  1122344556677889 9AABCCDDEFF 0112334456677889 9AABBCCDEEF
  7  0 14  1    -3.45580  011223445667788 99AABCCDDEFF 0112334456677889 9AABCCDEEFF
  7  0 14  6    -3.53939  00122344556678889AABBCDDEFF 01123345566788 89AABBCCDEEF0
  7  0 14 11    -3.61204  F0012344556677889 9ABBCDDEFF 0112334556778899AABBCCDEF00
  7  0 15  0    -3.69764  FF0123344556777899ABBCDDEFF 0112334556778999ABBCCDDEF01
  7  0 15  5    -3.76832  FF0112334556777899AABCCDEFF 0112344566778999ABBCDDEFF01
  7  0 15 10    -3.84597  EFF11233445667788 9AABCCDEFF 0112344566788999AABCCDDEFF11
  7  0 15 15    -3.92664  EEF0122334556778 89AABCCDEFF 011234456678899ABBCDDEEF012
  7  1  0  4    -3.99636  EEF00122345567778 9AABCCDEEF 0122344566789 99ABBCDEEF0012
  7  1  0  5    -4.00333  DEF00122345567778 9AABCCDEEF 01223445667899 9ABBCDEEF0012
  7  1  0  9    -4.07206  DEE001223445667789 9ABCCDEEF 01223445677899AABCCDEEF0022
  7  1  0 14    -4.15177  DDEF0122344556678 99ABBCDEEF 012234556778 9AABBCCDEEF0123
  7  1  1  3    -4.22749  CDEF011223455667889ABBCDEEF 0122345567889AABBCDEEFF0123
  7  1  1  8    -4.30721  CDEEF0112344566788 9ABBCDEEF 01223455678 89AABCCDEFF01223
  7  1  1 13    -4.38596  CCDEF01123345667789AABCDEEF 0122345667899AABCDDEFF01234
  7  1  2  2    -4.44875  BCDEE0012334556778 9AABCDDEF 012334566789 9ABBCDDEF002234
  7  1  2  7    -4.53549  BCCEE001223445667899ABCDDEF 01233456778 9AABCCDEEF002244
  7  1  2 12    -4.61526  BBCDEF011234455678 99ABCDDEF 01233456778 9ABBCCDEFF012345
  7  1  3  1    -4.69304  ABCDEF001223455678 89ABCDDEF 0123345678 89ABBCDEEF0012345
  7  1  3  6    -4.76386  ABBDDFF01123455678 89ABCCDEF 0123445678 89ABBCDEFF0113355
  7  1  3 11    -4.84265  AABCDEF00123455677 89ABCCDEF 01234456789 9ABBCDEF00123456
  7  1  4  0    -4.92346  9ABCDEFF0123345667 89ABCCDEF 012344567 89AABCDDEF0112345 6
  7  1  4  5    -5.00128  9AACCEFF012234556789ABBCDEF 0123455678 9ABBCDEEF01124466
  7  1  4 10    -5.08310  99ABCEEF011234456789ABBCDEF 0123455678 9ABCCDEFF01224567
  7  1  4 15    -5.15396  89ABCDEFF012344567 89AABCDEF 0123456678 9ABCCDEF011234567
  7  1  5  4    -5.22782  899BBDEEF012344567889ABCDEF 0123456[illegible]
 THUMBWHEEL      CRCTD                    PHASE SHIFTER STATES
 SWITCH          BEAM              LEFT                          RIGHT
SETTING          POS.     222222221111111111                     11111111112222222
                          765432109876543210987654321 012345678901234567890123456

  7  1   5  9   -5.28971  789ABDDEF012334567889ABCDEF 01234567889ABCDDEF012335678
  7  1   5 14   -5.38656  789ABCDEF011234566789ABCDEF 0123456789AABCDEFF012345678
  7  1   6  3   -5.47143  788AACDEF001234456789ABCDEF 0123456789ABCCDEF0012346688
  7  1   6  8   -5.54833  678AACDEEF01233456789ABCDEF 0123456789ABCDDEF0122346689
  7  1   6 13   -5.62824  6789ABCDEF01223456789ABCDEF 0123456789ABCDEEF0123456789
  7  1   7  2   -5.72215  6789ABCDDEF0123456789ABCDEF 0123456789ABCDEF01233456789
  7  1   7  7   -5.78909  56799BCCDEF0123456789ABCDEF 0123456789ABCDEF0123445779A
  8  0   0  0   -5.83306  56789ABCDEF0123456789ABCDEF 0123456789ABCDEF0123456789A
  8  0   0 11   -6.00109  46688ABCDEF01223456789BCDEF 012345789ABCDEEF012345688AA
  8  0   4 11   -6.99245  012456789BCDEF01345679ABCDF 01345679ABCDF012345789ABCEF
  8  0   4 12   -7.00742  012446789BCDEF01345679ABCDF 01345679ABCDF012345789ACCEF
  8  0   8 12   -7.99936  BCEF1245689ACDEF1235679ACDF 0134679ABDEF1234678ABCEF124
  8  0   8 13   -8.01738  BCEF1245679ACDEF1235679ACDF 0134679ABDEF1234679ABCEF124
  8  0  12 12   -8.99382  789BDF0235679BCDF023568ABDE 023568ABDE0134579ABDE013578
  8  0  12 13   -9.00990  789BDF0135679BCDF023568ABDE 023568ABDE0134579ABDF013578
  8  1   0 13  -10.00702  24579BDE0235689BDF024579BCE 024579BCE013578ABDE023579BC
  8  1   4 13  -11.00170  DF13579BDF024679BDF13468ACE 02468ACDF13579ACE013579BDF1
  9  0   0  0  -11.72769  ACE02468ACE02468ACE02468ACE 02468ACE02468ACE02468ACE024
  9  0   1  1  -12.00057  9BDF14679BEF24579BDF1368ACE 02468ADF13579BCE12579ACF135
  9  0   5  1  -13.00457  579BD02468ADF1357ACE02579BE 02579BE02469BDF1368ACE03579
  9  0   9  0  -14.00077  02479CF1358ACF1368ADF1469BE 0257ACF1368ADF1468BDF1479CE
  9  0  12 15  -14.99314  BE0369BD0357ACF1469BE0368BD 0358AD0257ACF1469BD0357AD02
  9  0  13  0  -15.01165  BE0369BD0257ACF1469BE0368BD 0358AD0257ACF1469BE0357AD02
  9  1   0 14  -16.00130  79CF258AD0257ACF257ADF258AD 0368BE1369BE1469BE0368BE147
  9  1   4 13  -17.00579  258BE147ADF258AD0369CE147AD 0369CF247AD0368BE1369CF258B
 10  0   0  0  -17.75159  F258BE147AD0369CF258BE147AD 0369CF258BE147AD0369CF258BE
 10  0   0 15  -17.99269  E147AE136AD0368BE147AD147AD 0369CF369CF258AD036ADF269CF
 10  0   1  0  -18.01140  E147AE1369D0368BE147AD147AD 0369CF369CF258AD037ADF269CF
 10  0   4 13  -18.99381  AD046AD037AD0369D0369C0369D 037AD047AD037AD0369D036AC03
 10  0   4 14  -19.00848  AD036AD037AD0369D0369C0369D 037AD047AD037AD0369D036AD03
 10  0   8 11  -20.00976  58C036AD047AE147BE158BF269D 037AE158BF259CF269C036AD048
 10  0  12  7  -20.99408  148CF37AD148BF259C037BE259C 047BE259D047BE158CF369D148C
 10  0  12  8  -21.01003  148BF37AD148BF259C037BE259C 047BE259D047BE158CF369D158C
 10  1   0  4  -21.99860  D048BF36AE259D037BF26AD158C 048BF36AE159D037BE26AD158C0
 10  1   0  5  -22.00610  C048BF36AE259D037BF26AD158C 048BF36AE159D037BE26AD158C0
 10  1   4  0  -22.99903  8C048C037BF36AE259D159D048C 048C037BF37BE26AD159D048C04
 10  1   4  1  -23.01091  8C048C037BF36AE259D159C048C 048C047BF37BE26AD159D048C04
 11  0   0  0  -23.98648  48C048C048C048C048C048C048C 048C048C048C048C048C048C048
 11  0   0  1  -24.00704  48C048C048C048CF48C048C048C 048C048C048C148C048C048C048
 11  0   3 12  -25.00111  048C159D159E26AE26AE37BF38C 048D159D26AE26AE27BF37BF48C
 11  0   7  7  -26.00577  C049D26AE27BF48C059D16AE37C 049D26AF37B048C159E26AE37C0
 11  0  11  1  -27.00242  8C059E37B049D26AF37C059E27C 049E27B049D16AE37C059D27B04
 11  0  14 11  -28.00323  38C16B049D26BF48D16BF49D27B 059E37C15AF38C15AE37C05AF48
 11  1   2  4  -28.99480  F49E28C16AF49D26B05AE38D16B 05AF38D26B05AE37C16AF48E27C
 11  1   2  5  -29.01298  F49E28C16AF49D26B059E38D16B 05AF38D27B05AE37C16AF48E27C
 11  1   5 13  -30.00552  B05AF49E38D16B05AF38D27C16B 05AF49E38D16B05AF38D27C16B0
 12  0   0  0  -30.54077  9E38D27C16B05AF49E38D27C16B 05AF49E38D27C16B05AF49E38D2
 12  0   1 10  -31.00011  7D17C16B05AF49E38D27C16B16B 05AF5AF49E38D27C16B05AF49F3
 12  0   5  1  -32.00002  49E38E38D27D27C16C16B06B05B 05B05A05AF4AF49E39E38D28D27
 12  0   8  7  -32.99681  05A05B05A05A05AF5AF5A05A05B 05B06B06B16B16B06B06B05B06B
 12  0   8  8  -33.01455  05A05A05A05A05AF5AF5A05A05B 05B06B06B16B16B06B06B06B06B
 12  0  11 14  -34.00358  C16C17D28D38E38E39E49F4AF5B 05B16C17C27D28D28D38E39F4AF
 12  0  15  4  -35.00258  8D39E4AF5B06C16C27D38E39F5A 06B17D28D39E4AF4A05B16C27D3
 12  1   2  9  -35.99615  49F5B27D38E49F5A06C17D39E4A 06C27D39F4A06B17C28D39E5B17
 12  1   2 10  -36.01335  49F5B17D38E49F5A06C17D39E4A 06C27D39F4A06B17C28D39F5B17
 12  1   5 13  -36.99273  06C28E4A06C17D39F5A06C28E4A 06C28E4A06B17D39F4A06C28E4A
 12  1   5 14  -37.01514  06C28E4A06C17D39F4A06C28E4A 06C28E4A06C17D39F4A06C28E4A
 THUMBWHEEL        CRCTD                   PHASE SHIFTER STATES
  SWITCH           BEAM                 LEFT                         RIGHT
 SETTING           POS.     222222221111111111                  11111111112222222
                            765432109876543210987654321 012345678901234567890123456

 13  0  0  0  -37.57371    E4A06C28E4A06C28E4A06C28E4A 06C28E4A06C28E4A06C28E4A06C
 13  0  1  5  -37.99925    D39F5C27D39F5B17D39F5B18E4A 06C28F5B17D39F5B17D39E4B17D
 13  0  1  6  -38.01683    D39F5B27D39F5B17D39F5B18E4A 06C28F5B17D39F5B17D39E5B17D
 13  0  4  9  -38.99991    9F5C28F4B17D39F5C28E4B17D3A 06D39F5C28E4B17D39F5C18E4B1
 13  0  4 10  -39.01904    9F5C28E4B17D39F5C28E4B17D3A 06D39F5C28E4B17D39F5C28E4B1
 13  0  7 11  -40.00445    6C28F5C28E5B18D4A07D3A06D3A 06D3A06D3906C38F5B28E4B18E4
 13  0 10 12  -40.99340    28F5C29F6C29F6C29F6C39F6C3A 06D4A17D4A17E4A17E4A17E4B18
 13  0 10 13  -41.01182    28F5C29F6C29F6C29F6C29F6C3A 06D4A17E4A17E4A17E4A17E4B18
 13  0 13 13  -41.99949    F5B2906D3A07D4A17E4B28F5C39 07D4B18E5C29F6C3906D3A07E5B
 13  0 13 14  -42.02222    F5B2906C3A07D4A17E4B28F5C39 07D4B18E5C29F6C3906D4A07E5B
 13  1  0 13  -42.99387    B28F6D4A18E5B28F6D3A17E5C29 07E4B29F6D3A18E5B28F6C3A18E
 13  1  0 14  -43.01425    B18F6D4A18E5B28F6D3A17E5C29 07E4B29F6D3A18E5B28F6C3A18F
 13  1  3 12  -43.98984    8E5C3A18E5C3A07E5B2907E4B29 07E5C2907E5B2906D4B28F6D4B2
 13  1  3 13  -44.00089    7E5C3A18E5C3A07E5B2907E4B29 07E5C2907E5B2906D4B28F6D4B2
 13  1  6 10  -44.99033    4B2908F5C3A18F5C3A18F6D4B29 07E5C3A18F6D4B18F6D4B1807E5
 13  1  6 11  -45.01283    4B2908E5C3A18F5C3A18F6D4B29 07E5C3A18F6D4B18F6D4B2807E5
 13  1  7  7  -45.28769    3A19F7E4B2907E5C3A18F6D4B29 07E5C3A18F6D4B2907E5C2917F6
 13  1  7  8  -45.30748    3A18F7E4B2907E5C3A18F6D4B29 07E5C3A18F6D4B2907E5C2918F6
 13  1  7  9  -45.33010    3A18F7D4B2907E5C3A18F6D4B29 07E5C3A18F6D4B2907E5C3918F6
```

```
CORRECTED BEAM ANGLES FOR SCAN PROGRAM 2
DATE: 23/01/84
FREQUENCY= 5060 MHZ


                                                                                 PAGE 1
 THUMBWHEEL        CRCTD                          PHASE SHIFTER STATES
 SWITCH            BEAM                 LEFT                                RIGHT
SETTING            POS.       222222221111111111                      11111111112222222
                              765432109876543210987654321 012345678901234567890123456

 0  0  0  0   45.69483   D6F81A3C5E7092B4D6F81A3C5E7 092B4D6F81A3C5E7092B4D6F81A
 0  0  0  1   45.66777   D6E81A3C5E7092B4D6F81A3C5E7 092B4D6F81A3C5E7092B4D6F82A
 0  0  0  2   45.64358   D6E71A3C5E7092B4D6F81A3C5E7 092B4D6F81A3C5E7092B4D6F92A
 0  0  0  3   45.61512   C6E71A3C5E7092B4D6F81A3C5E7 092B4D6F81A3C5E7092B4D6F92A
 0  0  2  0   44.99397   B4D6F92A3C6F81A3C5E7092B5E7 092B5E7092B4D6F81A4D6E71A3C
 0  0  4 14   44.00244   81A3C6F81B4D6F81B4D6F82B4D7 093C5E81A3C5F81A3C5F81A4D6F
 0  0  4 15   43.97751   81A3C6F81A4D6F81B4D6F82B4D7 093C5E81A3C5F81A3C6F81A4D6F
 0  0  7 12   43.00714   5D70A3D6F82B4E6092C5E81A4D7 093C6F82B4E70A2C5E81A3D6093
 0  0  7 13   42.99759   4D70A3D6F82B4E6092C5E81A4D7 093C6F82B4E70A2C5E81A3D6093
 0  0 10 12   42.00267   1A4D70A3D6F92C5E81B4E70A3D7 093D6092C5F82B4E71A3D6093C6
 0  0 10 13   41.98386   1A4D70A3D6F92C5E81B4D70A3D7 093D6093C5F82B4E71A3D6093C6
 0  0 13 12   41.00913   E71A4E71A4D70A3D6093D6093D6 0A3D70A3D70A3D6093C6F92C6F9
 0  0 13 13   40.99061   E70A4E71A4D70A3D6093D6093D6 0A3D70A3D70A3D6093C6F92C609
 0  1  0 14   40.00106   A3D71B5E82B5E81B5F82C5F93C6 0A4D71B4E81B5F82B5E82B5F93D
 0  1  0 15   39.97757   A3D71B5E81B5E81B5F82C5F93C6 0A4D71B4E81B5F82B5F82B5F93D
 0  1  4  0   38.99820   60A4E82B5F93C60A3D71B5F82C6 0A4E81B5F93D60A4D71B5E82C60
 0  1  7  1   37.99904   3D71B5F93C60A4E82C60A4E82C6 0A4E82C60A4E82C60A4D71B5F93
 1  0  0  0   37.83552   2C60A4E82C60A4E82C60A4E82C6 0A4E82C60A4E82C60A4E82C60A4
 1  0  2 11   37.00343   F93E82C60A4E83C61B5F93D71C6 0A4F93D71B5FA4D82C60A4E82D7
 1  0  2 12   36.97974   F93E82C60A4E83C60B5F93D71C6 0A4F93D71B50A4D82C60A4E82D7
 1  0  5 15   35.99936   C60A4F93D82C61B5F93E82C71B6 0A5F94E82D71B5FA4E83D71C60A
 1  0  9  3   35.00198   82C71C60B50A4F93D82D71C61B6 0A5FA4F93E83D71C60B50A4F94E
 1  0  9  4   34.97884   82C71C60B5FA4F93D82D71C61B6 0A5FA4F93E83D71C61B50A4F94E
 1  0 12  9   33.99888   4E93E93E83D82D71C61B61B60B5 0B50A5FA5FA4F93E83D82D72D72
 1  0 15 14   33.00798   0B50B60B50B50B50A50A50A50B5 0B50B60B60B60B50B50B50A50B5
 1  0 15 15   32.99130   0A50B60B50B50B50A50A50A50B5 0B50B60B60B60B50B50B50A50B6
 1  1  3  6   31.99568   C71D73D83D83E93E94E94FA4FA5 0B61C61C72C72D72D83D83D93F9
 1  1  6 12   31.00237   83E94FA50B61C71C72D83E94FA5 0B61C72D83E94F94FA50B61C72D
 1  1  6 13   30.98021   83E94FA50B61C61C72D83E94FA5 0B61C72D83E94FA4FA50B61C72D
 2  0  0  0   30.74140   72D83E94FA50B61C72D83E94FA5 0B61C72D83E94FA50B61C72D83E
 2  0  2 10   29.99736   4FA61C72D83EA5FA61C72D83EA5 0B62D83E94FA61B62D83E94FA61
 2  0  6  1   29.01046   1B72D94FA61C73D94FA61C73E95 0B72D94FA61C73D94FA61C73E95
 2  0  6  2   28.99336   1B62D94FA61C73D94FA61C73E95 0B72D94FA61C73D94FA61C73EA5
 2  0  9 10   28.00012   C73EA61C83EA50B72E940B72E95 0B72E950C72E950B62D84FA62D9
 2  0  9 11   27.98316   C73EA51C83EA50B72E940B72E95 0B72E950C72E950B62D84FB62D9
 2  0 13  4   26.99823   83FB62E950C73E951C83FA62D94 0C73EA61D84FB72D940B72EA51D
 2  1  0 14   25.99777   4FB73FB62E950C73FB62E951D84 0C83FB72EA51D940B72EA51D951
 2  1  4  8   24.99863   0B74FC73FB72EA51D951D940C84 0C840C73FB73FB62E951D941C95
 3  0  0  0   24.13771   C840C840C840C840C840C840C84 0C840C840C840C840C840C840C8
 3  0  0  7   24.00697   B73FB730C840C840C840C840C84 0C840C840C840C840C840D951D9
 3  0  0  8   23.99063   B73FB73FC840C840C840C840C84 0C840C840C840C840C841D951D9
 3  0  4  4   22.99397   83FC851D951D961EA62EA73FB74 0C951D962EA62FA73FB73FB841D
 3  0  7 15   22.00006   3FC851EA62EB73FC841D962EB74 0C952EA73FC841D952EA62FB841
 3  0  8  0   21.98176   3FC851E962EB73FC841D962EB74 0C952EA73FC841D952EA72FB841
 3  0 11 11   20.99487   FB841EA63FC851DA63FC851EA74 0C962FB841DA63FB841DA62FC85
 3  0 15  8   20.00408   A731DA730D962FB851EA740DA73 0D9630C962FB851EA730D963FD9
 3  0 15  9   19.98493   A731DA730D962FB841EA740DA73 0D9630C962FC851EA730D963FD9
 3  1  3  6   18.98918   63FD9730D9630D9630C9630C963 0DA740DA740DA730DA730D9731D
 3  1  7  1   17.99596   2FC9630DA630DA741EB852FC963 0DA741EB852FC9630DA630DA741
 4  0  0  0   17.86037   1EB852FC9630DA741EB852FC963 0DA741EB852FC9630DA741EB852
 4  0  3  5   16.99444   EB752FD9641EB852FC9741EB863 0DA852FC9741EB852FCA731EB95
 4  0  7  2   16.00581   A631EC9631EB9630DB8530DB853 0DB8530DB8530DA752FDA742FDA
 4  0  7  3   15.99958   9631EC9631EB9630DB8530DB853 0DB8530DB8530DA752FDA742FDA
 THUMBWHEEL         CRCTD                           PHASE SHIFTER STATES
  SWITCH            BEAM                   LEFT                                   RIGHT
 SETTING            POS.       222222221111111111                           11111111112222222
                               765432109876543210987654321 012345678901234567890123456

   4  0 11  1      15.00538    52FDA8630EB9641EC9641FCA753 0DB9641FCA742FCA7520DA8631E
   4  0 11  2      14.99711    42FDA8630EB9641EC9641FCA753 0DB9641FCA742FCA7520DA8631E
   4  0 14 15      14.00972    0EB97520DB8641ECA7530EC9752 0EB97420DB9642FCA8530EB9752
   4  0 15  0      13.99427    0DB97520DB8641ECA7530EC9752 0EB97420DB9642FCA8530EB9753
   4  1  2 15      13.00327    B97531FCA8631FCA8641FDB9642 0ECA7531FCA8641FDA8641FDB97
   4  1  3  0      12.98685    B97531FCA8631FCA8631FDB9642 0ECA7531FDA8641FDA8641FDB97
   4  1  6 13      12.00772    7531FDB97531FCA86420ECA8642 0ECA86420ECA8641FDB97531FDB
   4  1  6 14      11.98728    7531FDB97531ECA86420ECA8642 0ECA86420ECA8642FDB97531FDB
   5  0  0  0      11.79822    6420ECA86420ECA86420ECA8642 0ECA86420ECA86420ECA86420EC
   5  0  3  2      11.00518    31FDB986420ECA86420FDB97542 0ECB975310ECA86420ECA87531F
   5  0  3  3      10.99098    31EDB986420ECA86420FDB97542 0FCB975310ECA86420ECA87532F
   5  0  7  2       9.99150    FCA976420FDBA86421FDCA87532 0EDB986431FECA865310ECA9764
   5  0 11  3       8.98677    9865321FDCA976420FDCA976432 0EDCA9764310ECA976431FEDBA8
   5  0 15  1       8.00709    53210FDBA9765310FDCB9875431 0FDCB98754310FDBA9765310FED
   5  0 15  2       7.99296    5321FFDBA9765310FDCB9875431 0FDCB98754310FDBA9765311FED
   5  1  3  2       7.00185    0FEDBBA8764321FEDCA98765321 0FEDBA98764321FEDCA98655321
   5  1  3  3       6.98573    0FEDBB98764321FEDCA98765321 0FEDBA98764321FEDCA98755321
   5  1  7  1       5.99745    CBA987654210FEDCBA987654321 0FEDCBA9876543210FECBA98765
   6  0  0  0       5.86776    BA9876543210FEDCBA987654321 0FEDCBA9876543210FEDCBA9876
   6  0  0  3       5.81176    AA877654321 0FEDCBA987654321 0FEDCBA9876543210FEDCBA9986
   6  0  0  8       5.73277    A9876543321 0FEDCBA987654321 0FEDCBA9876543210FEDDCBA987
   6  0  0 13       5.66277    A9876543210FFDDCBA987654321 0FEDCBA98765433110FEDCBA987
   6  0  1  2       5.56078    A9876543210FEDCBA9987654321 0FEDCBA98776543210FEDCBA987
   6  0  1  7       5.49878    A9876543210FEDCBA9876544321 0FEDCCBA9876543210FEDCBA987
   6  0  1 12       5.43979    99765543210FEDCBA9876543321 0FEDDCBA9876543210FEDCBBA97
   6  0  2  1       5.35779    98765442100FEDCBA9876543321 0FEDDCBA98765432100FECCBA98
   6  0  2  6       5.27780    9876543210FFEDBAA9876543221 0FEEDCBA98766532110FEDCBA98
   6  0  2 11       5.26381    8766543210FEDDBAA9876543221 0FEEDCBA98766533210FEDCBAA9
   6  0  3  0       5.11881    8765443210FEDCBA99876543221 0FEEDCBA98876543210FEDCCBA9
   6  0  3  5       5.03782    8755433100FEDCBA98776543221 0FEEDCBA998765432100FDDCBB9
   6  0  3  8       4.99982    7755432100FEDCBA98766543221 0FEEDCBAA98765432100FEDCBB9
   6  0  3 10       4.96732    765543210FFEDCBA98766543221 0FEEDCBAA98765432110FEDCBBA
   6  0  3 15       4.88183    765433210FEDDCAA98766543221 0FEEDCBAA98766433210FEDDCBA
   6  0  4  4       4.81483    754433210FEDCCAA98765543211 0FFEDCBBA98766443210FEDDCCB
   6  0  4  9       4.73684    654432200FEDCBA998765543211 0FFEDCBBA987765432100EEDCCB
   6  0  4 14       4.66284    65432210FFEDCBA998765443211 0FFEDCCBA987765432110FEEDCB
   6  0  5  3       4.57485    64432210FEDDCBA987765443211 0FFEDCCBA998765433210FEEDCC
   6  0  5  8       4.50286    5433211FFEDCCBA987765443211 0FFEDCCBA998765443211FFEDDC
   6  0  5 13       4.42586    5432210FFEDCBBA987665433211 0FFEDDCBAA987655432110FEEDC
   6  0  6  2       4.34587    5322110FEEDCBB9987665433211 0FFEDDCBAA987755432210FFEED
   6  0  6  7       4.26587    4322110FEDDCBA9887655433211 0FFEDDCBBA988765433210FFEED
   6  0  6 12       4.18688    4321000EEDCCBA9887655433211 0FFEDDCBBA988765443222000FED
   6  0  7  1       4.10489    421100FEEDCBBA9877655433211 0FFEDDCBBA998765543222100FFE
   6  0  7  6       4.03789    321100FEDDCBAA9877654432211 0FFEEDCCBA998766543332100FFE
   6  0  7  8       4.00289    321100FEDCCBAA9876654432211 0FFEEDCCBAA98766544432100FFE
   6  0  7  9       3.98289    321100FEDCCBAA8876654432211 0FFEEDCCBAA98866544432100FFE
   6  0  7 11       3.95490    32100FFEDCCBAA8876654432211 0FFEEDCCBAA9886654432 1100FE
   6  0  8  0       3.87690    21100FFDDCBBA98876654432211 0FFEEDCCBAA98876554331100FF
   6  0  8  5       3.79491    2100FFEDDCBAA98776654432211 0FFEEDCCBAA99876654332 1100F
   6  0  8 10       3.72391    1000FEEDCCBAA98776554432211 0FFEEDCCBBA99876654432 21000
   6  0  8 15       3.64492    10FFFEEDCBBA998776554332211 0FFEEDDCBBA99877655432 21110
   6  0  9  4       3.56092    10FFEEDCCBAA998766554332211 0FFEEDDCBBAA98776654432 2110
   6  0  9  9       3.49093    0FFEEEDCCBAA988766544332211 0FFEEDDCCBAA98876654432 2211
   6  0  9 14       3.40494    0FFEDDDCBBA9987766544332211 0FFEEDDCCBAA99877655433 3211
   6  0 10  3       3.33094    0FEEDDCCBBA9987665544332111 0FFFEDDCCBBAA98776554433221
   6  0 10  8       3.26495    FEEEDDCBBAA9987665544322111 0FFFEEDCCBBAA98776655433222
   6  0 10 13       3.18285
```

```
                                                                            PAGE 3
  THUMBWHEEL        CRCTD                 PHASE SHIFTER STATES
   SWITCH           BEAM          LEFT                              RIGHT
  SETTING           POS.   22222222111111111                     11111111112222222
                           765432109876543210987654321 012345678901234567890123456

  6  0 11  2      3.11296  EEDDCCCBAA99887665443322111 0FFFEEDDCCBAA98877665444332
  6  0 11  7      3.02596  EDDDCCBBAA99876655443322111 0FFFEEDDCCBBAA9877665544333
  6  0 11  8      3.00596  EDDDCCBBAA98876655443322111 0FFFEEDDCCBBAA9887665544333
  6  0 11  9      2.98897  EDDDCCBAAA98876655443322111 0FFFEEDDCCBBAA9887666544333
  6  0 11 12      2.94197  EDCCCCBAA998876655443322111 0FFFEEDDCCBBAA9887766544443
  6  0 12  1      2.86897  DDCCBBBA9998776655443322111 0FFFEEDDCCBBAA9987776555443
  6  0 12  6      2.79698  DCCCBBBA9988776554443322110 00FFEEDDCCCBBA9988776555444
  6  0 12 11      2.72598  DCBBBBAA9988776554433222110 00FFEEEDDCCBBA9988776655554
  6  0 13  0      2.64499  CCBBBBA99887766554433222110 00FFEEEDDCCBBAA998877655554
  6  0 13  5      2.57300  CBBBAAA99887765554433221110 00FFFEEDDCCBBBA998877666555
  6  0 13 10      2.48400  CBBAAAA98877665544433221110 00FFFEEDDCCCBBAA99887666655
  6  0 13 15      2.41401  BBAAAA988877665544333221110 00FFFEEDDDCCBBAA99888766665
  6  0 14  4      2.33901  BAAA99988777665544332221110 00FFFEEEDDCCBBAA99988777666
  6  0 14  9      2.25902  AAA999988776655444332221110 00FFFEEEDDCCCBBAA9988777766
  6  0 14 14      2.17502  AA9999887766655443332221110 00FFFEEEDDDCCBBAAA998877776
  6  0 15  3      2.09503  A99988877766654443332221110 00FFFEEEDDDCCCBAAA999888777
  6  0 15  8      2.02804  998988877766554443322211110 00FFFFEEEDDCCCBBAA999888787
  6  0 15 10      1.99204  998988877666554433322211110 00FFFFEEEDDDCCBBAAA99888787
  6  0 15 13      1.94303  998888777665554433322211110 00FFFFEEEDDDCCBBBAA99988887
  6  1  0  2      1.87703  988877776665554433322211100 000FFFEEEEDDDCCBBBAAA999888
  6  1  0  7      1.79803  888877766665544333222211100 000FFFEEEEDDDCCBBAAAA999888
  6  1  0 12      1.71902  887777766655543333222111100 000FFFFEEEDDDDCBBBAAA999998
  6  1  1  1      1.63402  877777666555443332222111100 000FFFFEEEEDDDCCBBBAAA99999
  6  1  1  6      1.56002  777766665554443332222111100 000FFFFEEEEDDDCCCBBBAAAA999
  6  1  1 11      1.48301  776666655554443322221111100 000FFFFFEEEEDDCCCBBBBAAAAA9
  6  1  2  0      1.40901  766656655544433322221111000 0000FFFFEEEEDDDCCCBBBAABAAA
  6  1  2  5      1.33401  666656555444433222211111000 0000FFFFFEEEEDDCCCCBBBABAAA
  6  1  2 10      1.25700  655555555444333222211111000 0000FFFFFEEEEDDDCCCBBBBBBBB
  6  1  2 15      1.17700  555555544443322222211111000 0000FFFFFEEEEEDDDCCCCBBBBBB
  6  1  3  4      1.10200  555545444433322222111110000 00000FFFFFEEEEDDDDCCCCBCBBB
  6  1  3  9      1.02399  544445444333332221111110000 00000FFFFFFEEEDDDDDCCCBCCCC
  6  1  3 11       .99199  544444443333332221111110000 00000FFFFFFEEEDDDDDDCCCCCCC
  6  1  3 14       .94699  444444443333322211111110000 00000FFFFFFFEEEDDDDDCCCCCCC
  6  1  4  3       .86699  443444433333222111111100000 000000FFFFFFFEEEDDDDDCCCCDC
  6  1  4  8       .78299  433434333332221111111100000 000000FFFFFFFFEEEDDDDDCDCDD
  6  1  4 13       .71599  333333333322221111111000000 0000000FFFFFFFEEEEDDDDDDDDD
  6  1  5  2       .63699  332333322222221111110000000 00000000FFFFFFEEEEEEEDDDDED
  6  1  5  7       .55800  322223322222211111100000000 000000000FFFFFFEEEEEEDDEEEE
  6  1  5 12       .48400  222222222222111111000000000 0000000000FFFFFFEEEEEEEEEEE
  6  1  6  1       .39600  222212222211111100000000000 000000000000FFFFFFEEEEEFEEE
  6  1  6  6       .30900  211212222111110000000000000 00000000000000FFFFFEEEEFEFF
  6  1  6 11       .23900  111112111111110000000000000 00000000000000FFFFFFFFEFFFF
  6  1  7  0       .14700  111111111100000000000000000 000000000000000000FFFFFFFFF
  6  1  7  5       .06600  110101100000000000000000000 000000000000000000000FF0F0F
  7  0  0  0       .00000  000000000000000000000000000 000000000000000000000000000
  7  0  0  1      -.01890  00F000000000000000000000000 000000000000000000000000010
  7  0  0  5      -.08854  FFFF00F00000000000000000000 000000000000000000000100111
  7  0  0 10      -.15519  FFFFFFFFF000000000000000000 000000000000000000111111111
  7  0  0 15      -.23082  FFFFFFFFFFFFFF0000000000000 000000000000011111111111111
  7  0  1  4      -.31839  FFFFFFFFFFFFFFFFFFF00000000 000000001111111111111111111
  7  0  1  9      -.38309  EFFFFFFFFFFFFFFFFFFFFFFF000 000011111111111111111111111
  7  0  1 14      -.45675  EEEEEFFEFFFFFFFFFFFFFFFF000 000011111111111111112112222
  7  0  2  3      -.54237  EEEEEEEEEFFFFEFFFFFFFFFF000 000011111111121111222222222
  7  0  2  8      -.61407  DEEEEEEEEEEFFEEFFFFFFFFFF00 000111111111221122222222222
  7  0  2 13      -.69473  DCDEDEEEEEEEFEEEFFFFFFFFF00 000111111112221222222223233
  7  0  3  2      -.77740  DDDDDDEEEEEEEEEEEEEFFFFFF00 000111111222222222222233333
  7  0  3  7      -.84812  CDCDDDDDDEEEEEEEEEEFFFFFF00 000111111222222222233333343
```

```
                                                                                   PAGE 4
THUMBWHEEL        CRCTD                        PHASE SHIFTER STATES
 SWITCH           BEAM                  LEFT                                 RIGHT
SETTING           POS.     222222221111111111                       1111111111222222
                           765432109876543210987654321 012345678901234567890123456

 7  0  3 12      -.92883   CCCCDDDDDDEEEEEEEEEEFFFFF00 000111112222222223333333444
 7  0  4  0      -.99658   CCCCCDDDDDDEEDEEEEEEEFFFF00 000111122222232233333334444
 7  0  4  1     -1.01551   CCCCCDDDDDDDDEDEEEEEEEFFF00 000111122222232333333334444
 7  0  4  6     -1.07032   BBBCCCDDDDDDEDEEEEEEEFFFFF0 001111122222232333333344455
 7  0  4 11     -1.15903   BBBCCCCCCDDDDDDDEEEEEFFFFF0 001111122222333333344444455
 7  0  5  0     -1.23678   BBBBBCCCCCDDDDDDDEEEEEFFFF0 001111222223333333444445555
 7  0  5  5     -1.32053   BAABBCCCCCCCDDDDDDEEEEFFFF0 001111222233333344444445566
 7  0  5 10     -1.38933   AAAABBBBCCCCDDDDDDEEEEFFFF0 001111222233333344445555666
 7  0  5 15     -1.46811   AAAAABBBBCCCCDDDDDDEEEEFFF0 001112222333333444455556666
 7  0  6  4     -1.55389   A99AABBBBBCCCCCDDDDEEEEFFF0 001112222333344444555556677
 7  0  6  9     -1.62870   9999ABBBBBBCCCCCDDDDEEEFFF0 001112223333444445555556777
 7  0  6 14     -1.71251   99999ABABBBBCCCCCDDDEEEFFF0 001112223334444455556567777
 7  0  7  3     -1.78035   88899AAAABBBCCCCCDDDEEEFFF0 001112223334444455566667788
 7  0  7  8     -1.85820   88899AAAAABBBCCCCCDDDEEEFF0 001122233344444555666667788
 7  0  7 13     -1.92906   778899AAAABBBCBCCCDDDEEEFF0 001122233344454555666677889
 7  0  8  1     -1.99794   778889A9AAABBBBCCCDDDEEEFF0 001122233344455556667678889
 7  0  8  2     -2.01391   77888999AAABBBBCCCDDDEEEFF0 001122233344455556667778889
 7  0  8  7     -2.10077   777889999AAABBBBCCCDDEEEFF0 001122233444555566677778899
 7  0  8 12     -2.16368   667788999AAABBBBCCCDDDEEFF0 00112233344455556667778899A
 7  0  9  1     -2.24556   6667788999AAABBBCCCDDDEEFF0 0011223334445556667778899AA
 7  0  9  6     -2.32146   56677888999AABBBBCCCDDEEFF0 0011223344455556677788899AA
 7  0  9 11     -2.40438   55667788999AAAABBCCCDDEEFF0 001122334445566667778899AAB
 7  0 10  0     -2.48730   555667888999AAABBBCCDDEEFF0 00112233445556667778889AABB
 7  0 10  5     -2.55425   455667788899AAAABBCCDDEEEF0 001222334455666677888 99AABB
 7  0 10 10     -2.62919   4455677788999AAABBCCDDDEEF0 00122333445566677788999ABBC
 7  0 10 15     -2.70816   4445667778899AAABBCCCDDEEF0 0012233444556667788999AABCC
 7  0 11  4     -2.78512   3445567778899A9AABBCCDDEEF0 0012233445566767788999ABBCC
 7  0 11  9     -2.87110   334556667888999AABBCCDDEEF0 00122334455667778889AAABBCD
 7  0 11 14     -2.94609   333445667788999AABBCCDDEEF0 00122334455667778899AABCCDD
 7  0 12  1     -2.99110   233445666788899AABBCCDDEEF0 0012233445566778889AAABCCDD
 7  0 12  3     -3.01209   233445666778899AABBCCDDEEFF 0112233445566778899AAABCCDD
 7  0 12  8     -3.09311   2233456667788999AABBCDDEEFF 0112233455667778899AAABCDDE
 7  0 12 13     -3.17012   2223455567778999AABBCCDEEFF 0112234455667778999ABBBCDEE
 7  0 13  2     -3.25016   1223445566778889AABBCCDEEFF 011223445566788899AABBCCDEE
 7  0 13  7     -3.32020   11223455667788899ABBCCDDEFF 011233445567788899AABBCDEEF
 7  0 13 12     -3.40827   11223445566778899AABCCDDEFF 01123344566778899AABBCCDEEF
 7  0 14  1     -3.47632   01122344566778899AABCCDDEFF 01123344566778899AABCCDEEFF
 7  0 14  6     -3.56040   00122344556678889AABBCDDEFF 0112334556678889AABBCCDEEF0
 7  0 14 11     -3.63348   F00123445566778899ABBCDDEFF 0112334556778899AABBCCDEF00
 7  0 15  0     -3.71959   FF0123344556777899ABBCDDEFF 0112334556778999ABBCCDDEF01
 7  0 15  5     -3.79069   FF0112334556777899AABCCDEFF 0112344566778999ABBCDDEFF01
 7  0 15 10     -3.86881   EFF112334456677889AABCCDEFF 011234456678899AABCCDDEFF11
 7  0 15 15     -3.94996   EEF012233455677889AABCCDEFF 011234456678899ABBCDDEEF012
 7  1  0  3     -4.00306   EEF001233455677789AABCCDEEF 012234456678999ABBCDDEF0012
 7  1  0  4     -4.02009   EEF001223455677789AABCCDEEF 012234456678999ABBCDEEF0012
 7  1  0  9     -4.09625   DEE0012234456677899ABCCDEEF 01223445677899AABCCDEEF0022
 7  1  0 14     -4.17643   DDEF012234455667899ABBCDEEF 0122345567789AABBCCDEEF0123
 7  1  1  3     -4.25260   CDEF011223455667889ABBCDEEF 0122345567889AABBCDEEFF0123
 7  1  1  8     -4.33280   CDEEF01123445667889ABBCDEEF 0122345567889AABCCDEFF01223
 7  1  1 13     -4.41201   CCDEF01123345667789AABCDEEF 0122345667899AABCDDEEF01234
 7  1  2  2     -4.47518   BCDEE00123345567789AABCDDEF 0123345667899ABBCDDEF002234
 7  1  2  7     -4.56244   BCCEE001223445667899ABCDDEF 012334567789AABCCDEEF002244
 7  1  2 12     -4.64268   BBCDEF01123445567899ABCDDEF 012334567789ABBCCDEFF012345
 7  1  3  1     -4.72092   ABCDEF00122345567889ABCDDEF 012334567889ABBCDEEF0012345
 7  1  3  6     -4.79217   ABBDDFF0112345567889ABCCDEF 012344567889ABBCDEFF0113355
 7  1  3 11     -4.87143   AABCDEF0012345567789ABCCDEF 012344567899ABBCDEF00123456
 7  1  4  0     -4.95272   9ABCDEFF012334566789ABCCDEF 01223445
 THUMBWHEEL       CRCTD                    PHASE SHIFTER STATES
  SWITCH          BEAM               LEFT                             RIGHT
 SETTING          POS.    222222221111111111                   1111111111222222
                          76543210987654321098 7654321 01234567890123456789 0123456

  7  1  4  3   -4.99688   9AACDEFF012334556789ABBCDEF 01234556789ABBCDDEF01123466
  7  1  4  4   -5.01695   9AACDEFF012234556789ABBCDEF 01234556789ABBCDEEF01123466
  7  1  4  5   -5.03101   9AACCEFF012234556789ABBCDEF 01234556789ABBCDEEF01124466
  7  1  4 10   -5.11332   99ABCEEF011234456789ABBCDEF 01234556789ABCCDEFF01224567
  7  1  4 15   -5.18460   89ABCDEFF01234456789AABCDEF 01234566789ABCCDEF011234567
  7  1  5  4   -5.25890   899BBDEEF012344567889ABCDEF 01234567889ABCCDEF012235577
  7  1  5  9   -5.32117   789ABDDEF012334567889ABCDEF 01234567889ABCDDEF012335678
  7  1  5 14   -5.41859   789ABCDEF011234566789ABCDEF 0123456789AABCDEFF012345678
  7  1  6  3   -5.50397   788AACDEF001234456789ABCDEF 0123456789ABCCDEF0012346688
  7  1  6  8   -5.58133   678AACDEEF01233456789ABCDEF 0123456789ABCDDEF0122346689
  7  1  6 13   -5.66172   6789ABCDEF01223456789ABCDEF 0123456789ABCDEEF0123456789
  7  1  7  2   -5.75619   6789ABCDDEF0123456789ABCDEF 0123456789ABCDEF01233456789
  7  1  7  7   -5.82353   56799BCCDEF0123456789ABCDEF 0123456789ABCDEF0123445779A
  8  0  0  0   -5.86776   56789ABCDEF0123456789ABCDEF 0123456789ABCDEF0123456789A
  8  0  0  8   -6.00278   456789ABDEF0123456789ABCDEF 0123456789ABCDEF012356789AB
  8  0  4  9   -7.00098   01245688ABCDEF01345679ABCDF 01345679ABCDF012345688ABCEF
  8  0  8  8   -7.99873   CDE01245689ACDEF1235689ACDF 0134678ABDEF1234678ABCEF023
  8  0  8  9   -8.01284   CCE01245689ACDEF1235689ACDF 0134678ABDEF1234678ABCEF024
  8  0 12  9   -9.00107   78ABDF0235689BCDF023578ABDE 0235689BDE0134578ABDE013568
  8  1  0  9  -10.00097   24589BDE023578ABDF024679BCE 024579ACE0135689BDE023578BC
  8  1  4  8  -10.99949   EF14589BDF124679BDF13568ACE 02468ABDF13579ACEF13578BCF1
  8  1  4  9  -11.01782   EF14589BDF024679BDF13568ACE 02468ABDF13579ACE013578BCF1
  9  0  0  0  -11.79822   ACE02468ACE02468ACE02468ACE 02468ACE02468ACE02468ACE024
  9  0  0 13  -12.00258   9BDF13579BDF2368ACE02468ACE 02468ACE02468ADE13579BDF135
  9  0  4 12  -13.00018   579CD02469BDF1358ACE03579BE 02579BD02468BDF1357ACE03479
  9  0  8 11  -14.00320   0258ACF1368ADF1368ADF1469BE 0257ACF1368ADF1368ADF1468BE
  9  0 12 10  -15.00450   CE1369BE0358ADF1469BE0368BD 0358AD0257ACF1368BD0257ADF2
  9  1  0  8  -16.00096   7AD0258AD0258ADF257AD0258AD 0368BE0369BE1368BE0368BE036
  9  1  4  6  -17.00303   368CE247AD0258BD0369CF147AD 0369CF147AD0358BE0369CE248A
 10  0  0  0  -17.86037   F258BE147AD0369CF258BE147AD 0369CF258BE147AD0369CF258BE
 10  0  0  8  -18.00153   E147AD037AD0369CF258BE147AD 0369CF258BE147AD0369D0369CF
 10  0  4  7  -19.00850   AD047AE147AD0469D0369D0369D 037AD037AD037AC0369CF269C03
 10  0  8  3  -20.00392   69C037AD147BE148BE258CF269D 037AE148BE258CF259CF369D047
 10  0 11 15  -21.00249   258CF37AD158CF269D047BE259D 037BE259C037AE148BF369D148B
 10  0 15 12  -22.00970   D148C047BE259D047BF26AD159C 047BF36AE159C037BE259C048CF
 10  1  3  8  -23.00528   9C058D048BF37BE269D159D048C 048C037BF37AE259D158C038B04
 10  1  7  1  -23.99643   59D159D158C048C048C048C048C 048C048C048C048C048BF37BF37
 10  1  7  2  -24.01614   59D159D148C048C048C048C048C 048C048C048C048C048CF37BF37
 11  0  0  0  -24.13771   48C048C048C048C048C048C048C 048C048C048C048C048C048C048
 11  0  3  2  -24.99246   159D15AE26AE26AE26AF37BF38C 048D159D16AE26AE26AE26BF37B
 11  0  3  3  -25.00785   158D15AE26AE26AE26AF37BF38C 048D159D16AE26AE26AE26BF38B
 11  0  6 13  -26.00836   D159D27AF37B048C159D26AF37C 049D16AE37BF48C059D169E37BF
 11  0 10  7  -26.99625   8C16AF38C059E26AF38C159E27C 049E27BF48D16AE27B048D16AF4
 11  0 10  8  -27.01416   8C16AF37C059E26AF38C159E27C 049E27BF48D16AE27B049D16AF4
 11  0 14  1  -28.00621   49D26B049E27B049D26B049D27B 059E37C05AE37C059E27C05AE37
 11  1  1  9  -28.99333   059E38D16B049E27C05AF38D26B 05AE38D16B049E27C05AF38D27B
 11  1  1 10  -29.01047   059E38D16B049E27C05AE38D26B 05AE38D26B049E27C05AF38D27B
 11  1  5  2  -30.00308   C15B05AE38D27C05AF49D27C16B 05AF49E37C16B049E38D26B05BF
 12  0  0  0  -30.74140   9E38D27C16B05AF49E38D27C16B 05AF49E38D27C16B05AF49E38D2
 12  0  0 15  -31.01033   8D27C16B05AF49E49E38D27C16B 05AF49E38D27C27C16B05AF49E3
 12  0  4  7  -32.01721   49E49E49E38D28C17C16B16B05B 05B05AF5AF49F48E38D27C27C27
 12  0  7 12  -33.00445   15B06B16B06B06A05A05A05A05B 05B06B06B06B06A05A05AF5A05B
 12  0 11  3  -34.01592   C27D28E38E39E49E39E49F4AF5B 05B16C17C27D27C27D28D28E39E
 12  0 14  7  -34.99527   9E49F5B06B16C27C28D38E49F5A 06B17C28D38E49E4AF5A05B17C2
 12  0 14  8  -35.01967   9E49F5B06B16C17C28D38E49F5A 06B17C28D38E49F4AF5A05B17C2
 12  1  1 12  -35.99825   5A06C28D39F4A05B06C27D39F4A 06C17D39E4A05B06C17D38E4A06
 12  1  1 13  -36.02173   5A06C28D39E4A05B06C27D39F4A 06C17D39E4A05B06C27D38E4A06
```

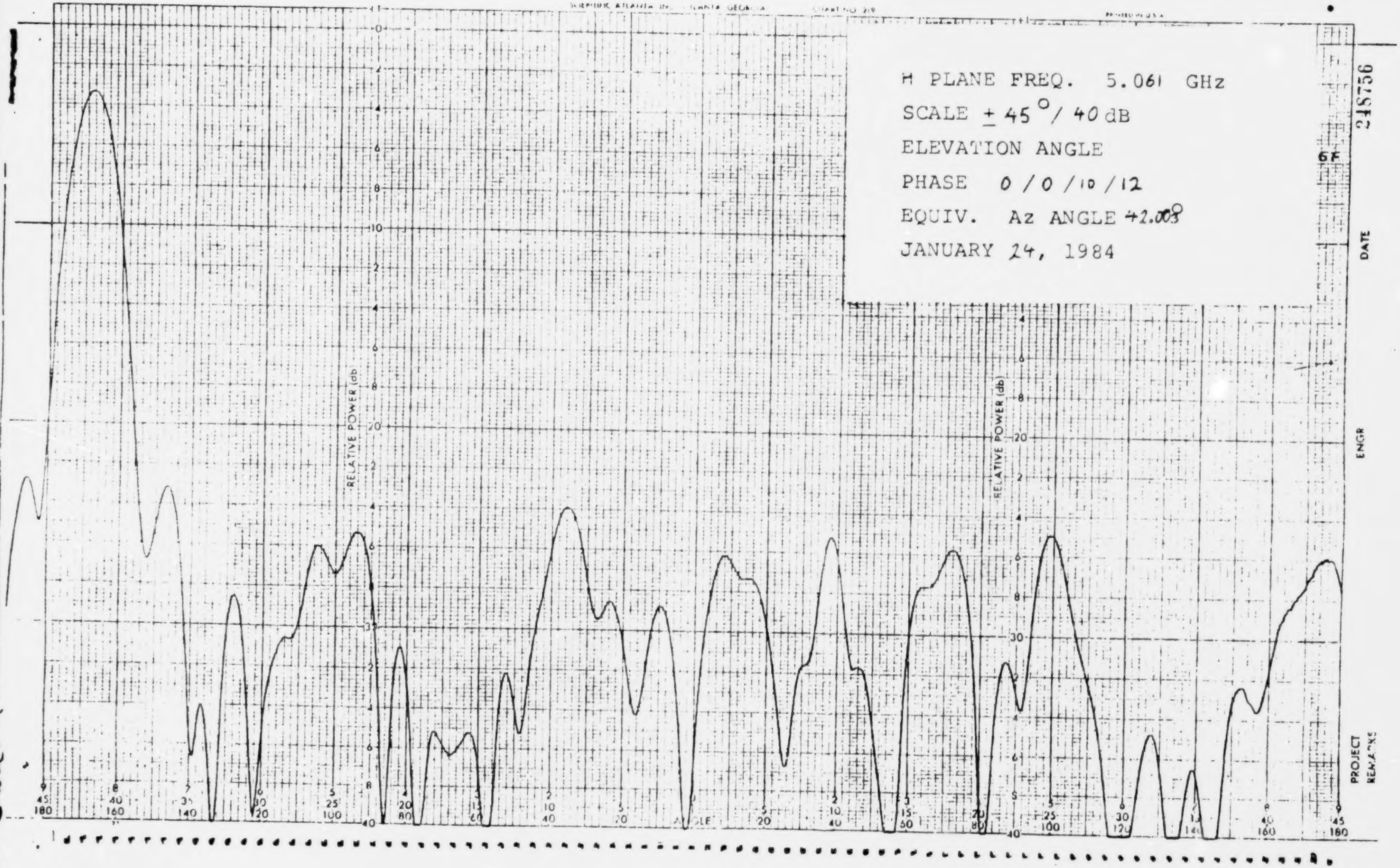
```
                                                                                   PAGE 6
 THUMBWHEEL        CRCTD                        PHASE SHIFTER STATES
 SWITCH            BEAM                  LEFT                                RIGHT
SETTING            POS.      222222221111111111                       11111111112222222
                             765432109876543210987654321 012345678901234567890123456

12  1  5  0   -36.99575     17D39F5B06C28E39F5B16C28E4A 06C28E4AF5B17D28E4A05B17D39
12  1  5  1   -37.01328     17C39F5B06C28E39F5B16C28E4A 06C28E4AF5B17D28E4A05B17D49
13  0  0  0   -37.83552     E4A06C28E4A06C28E4A06C28E4A 06C28E4A06C28E4A06C28E4A06C
13  0  0  8   -38.00577     D39F5B17E4A06C28E4A06C28E4A 06C28E4A06C28E4A06C29F5B17D
13  0  3 11   -39.00320     A06D39F5B17E4A06C28E5B17D4A 06C39F5B28E4A06C29F5B17D3A0
13  0  6 13   -40.01349     7D39F6D29F5B28E4B17D4A07D3A 06D3906C39F5C28E5B17E3A17D3
13  0  9 13   -40.99502     3906D3A06D3906C3906C3906D3A 06D3A07D4A07D4A07D3A06D3A07
13  0  9 14   -41.01353     3906C3A06D3906C3906C3906D3A 06D3A07D4A07D4A07D3A06D4A07
13  0 12 15   -42.00292     F6C3A17D4B17E4B18E5B28F6C39 07D4A18E5B28F5C29F5C39F6D4A
13  0 15 14   -43.00309     C3907E4B18F5C3906D4A18E5C39 07D4B28F6C3A07D4B18F5C2907D
13  1  2 13   -43.99813     9F6D4B28F6D4A17E5C3907E5B29 07E5B2907D4B29F6C3A18E5C3A1
13  1  2 14   -44.02454     9F6D4B28F6D3A17E5C3907E5B29 07E5B2907D4B29F6D3A18E5C3A1
13  1  5 12   -45.00613     5C3A18F6D4B28F6D4B18F6D4B29 07E5C3A18F5C3A18E5C3A18F6D4
13  1  7  7   -45.63187     3A19F7E4B2907E5C3A18F6D4B29 07E5C3A18F6D4B2907E5C2917F6
13  1  7  8   -45.65189     3A18F7E4B2907E5C3A18F6D4B29 07E5C3A18F6D4B2907E5C2918F6
13  1  7  9   -45.67479     3A18F7D4B2907E5C3A18F6D4B29 07E5C3A18F6D4B2907E5C3918F6
```

APPENDIX 2

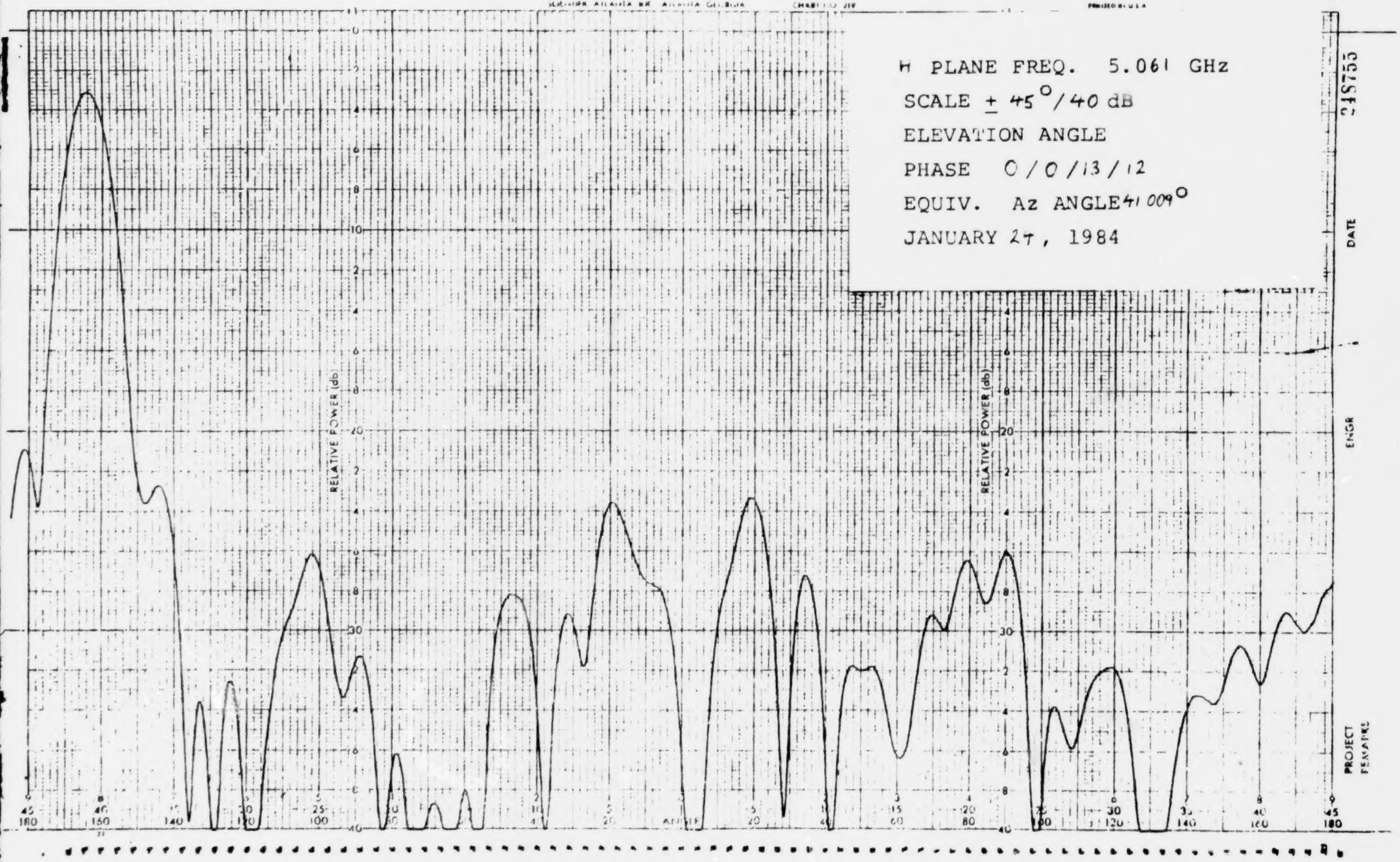
Azimuth Radiation Patterns

for

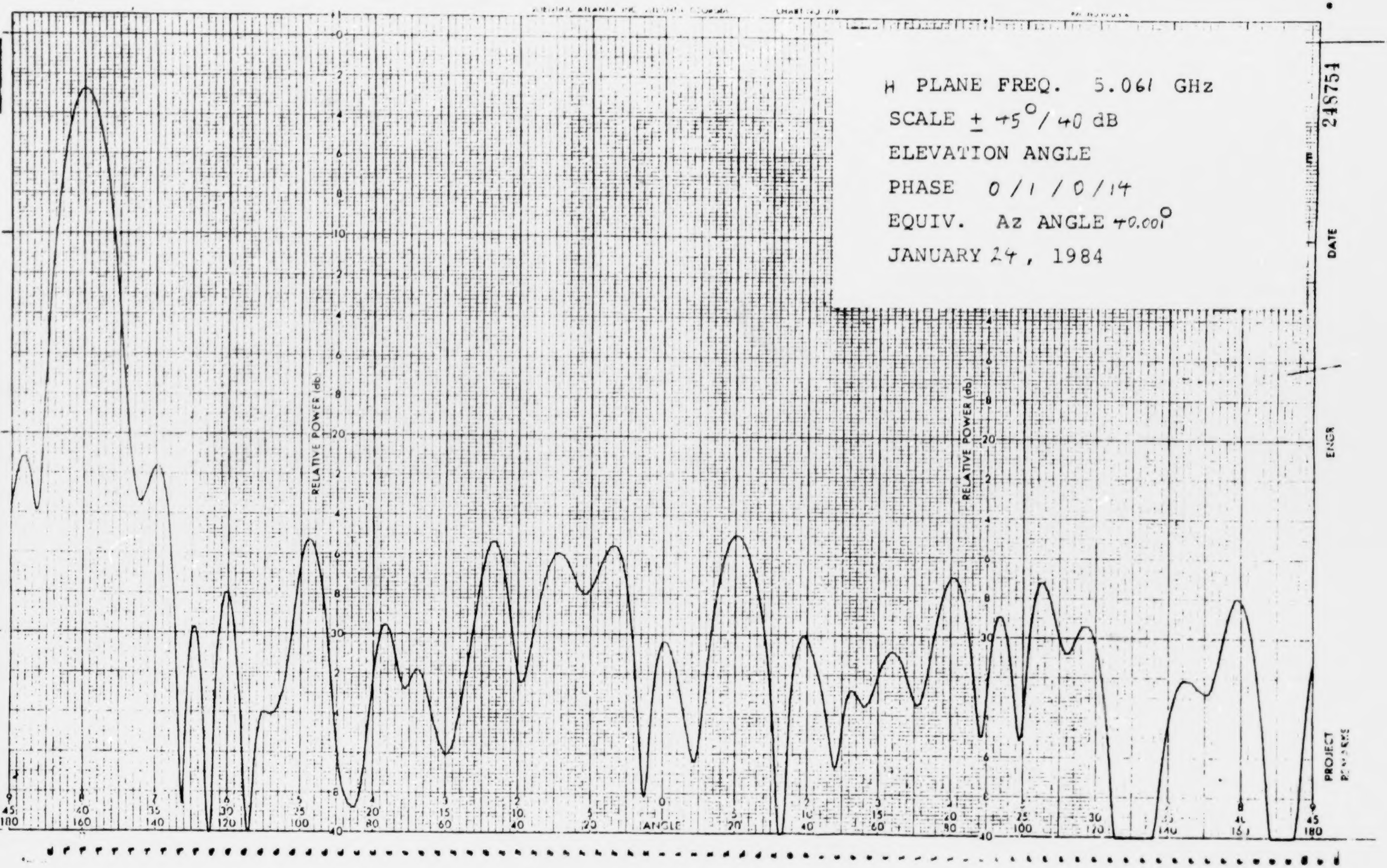
1 degree from -42° to $+42^{\circ}$ at 5060 MHz



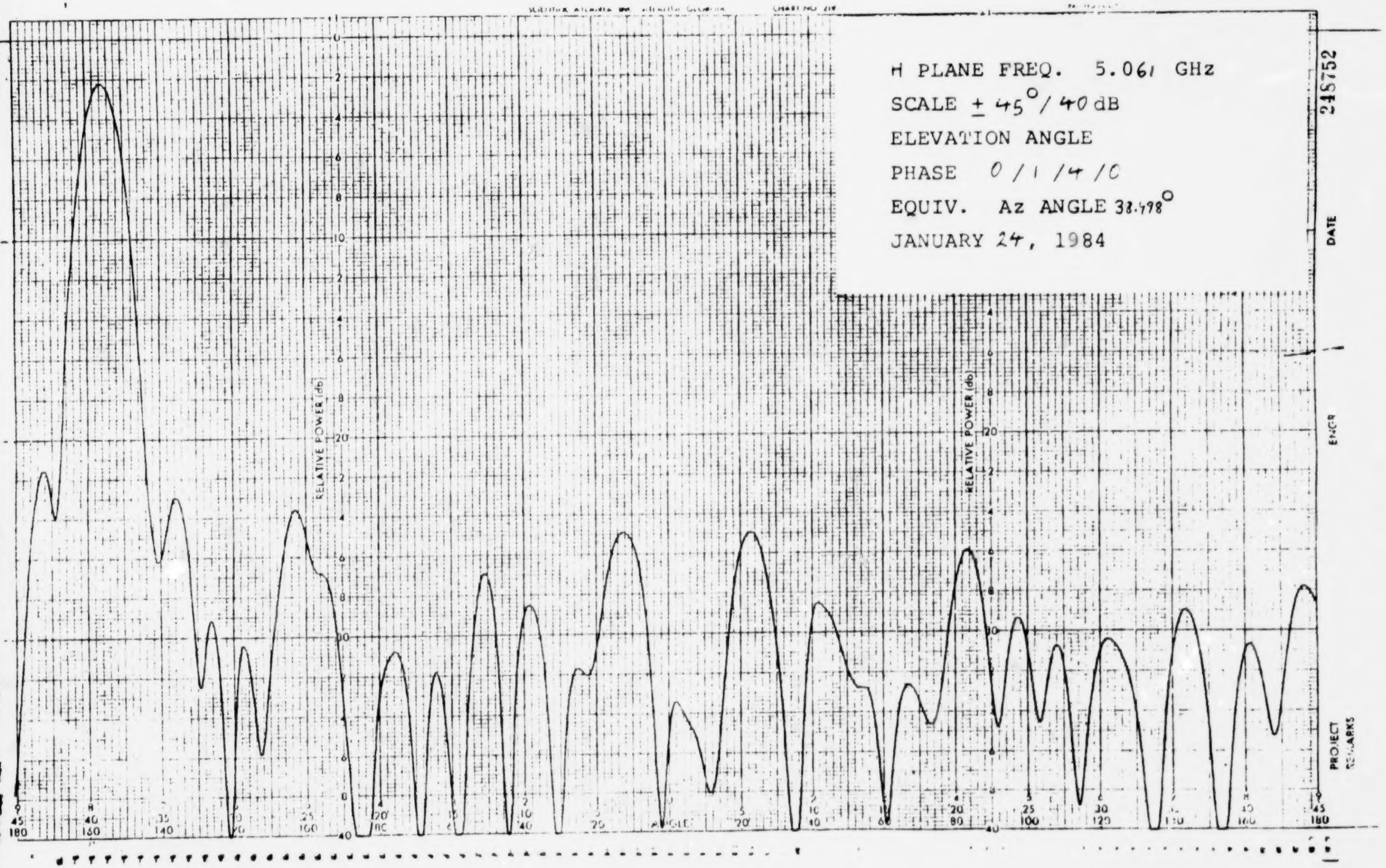
H PLANE FREQ. 5.061 GHz
SCALE ± 45°/ 40 dB
ELEVATION ANGLE
PHASE 0 / 0 / 10 / 12
EQUIV. Az ANGLE +2.003°
JANUARY 24, 1984



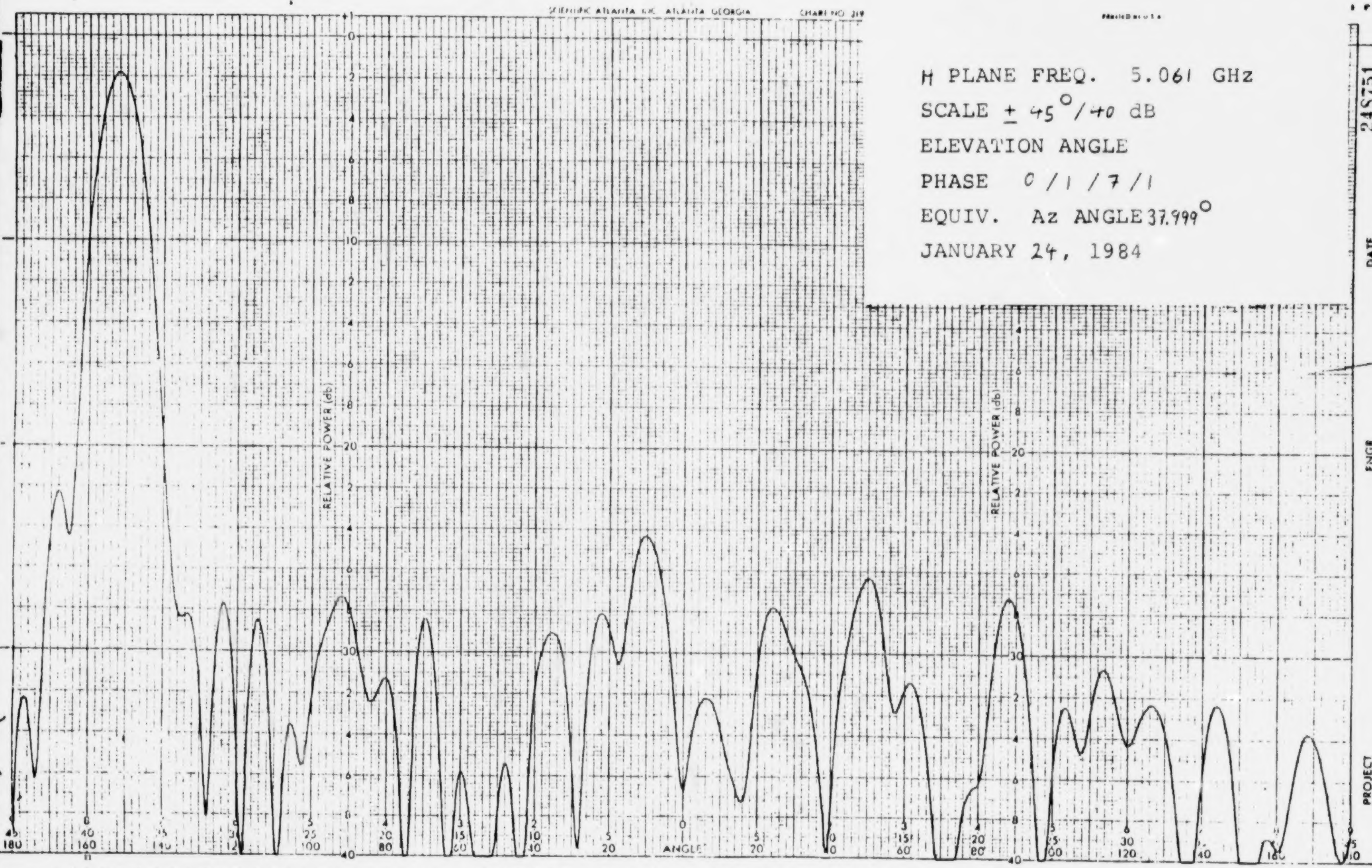
H PLANE FREQ. 5.061 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 0/0/13/12
EQUIV. Az ANGLE 41.009°
JANUARY 24, 1984

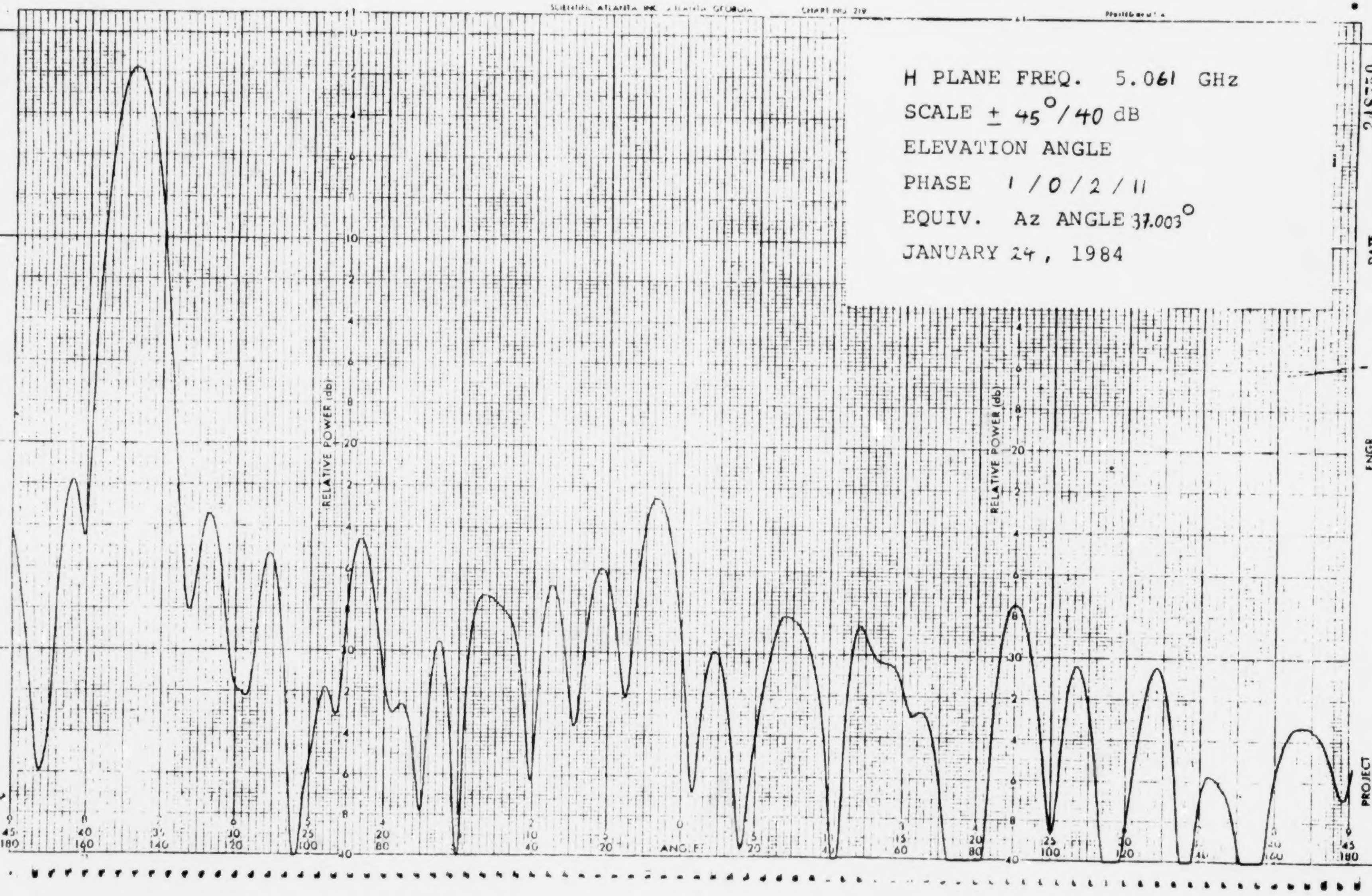


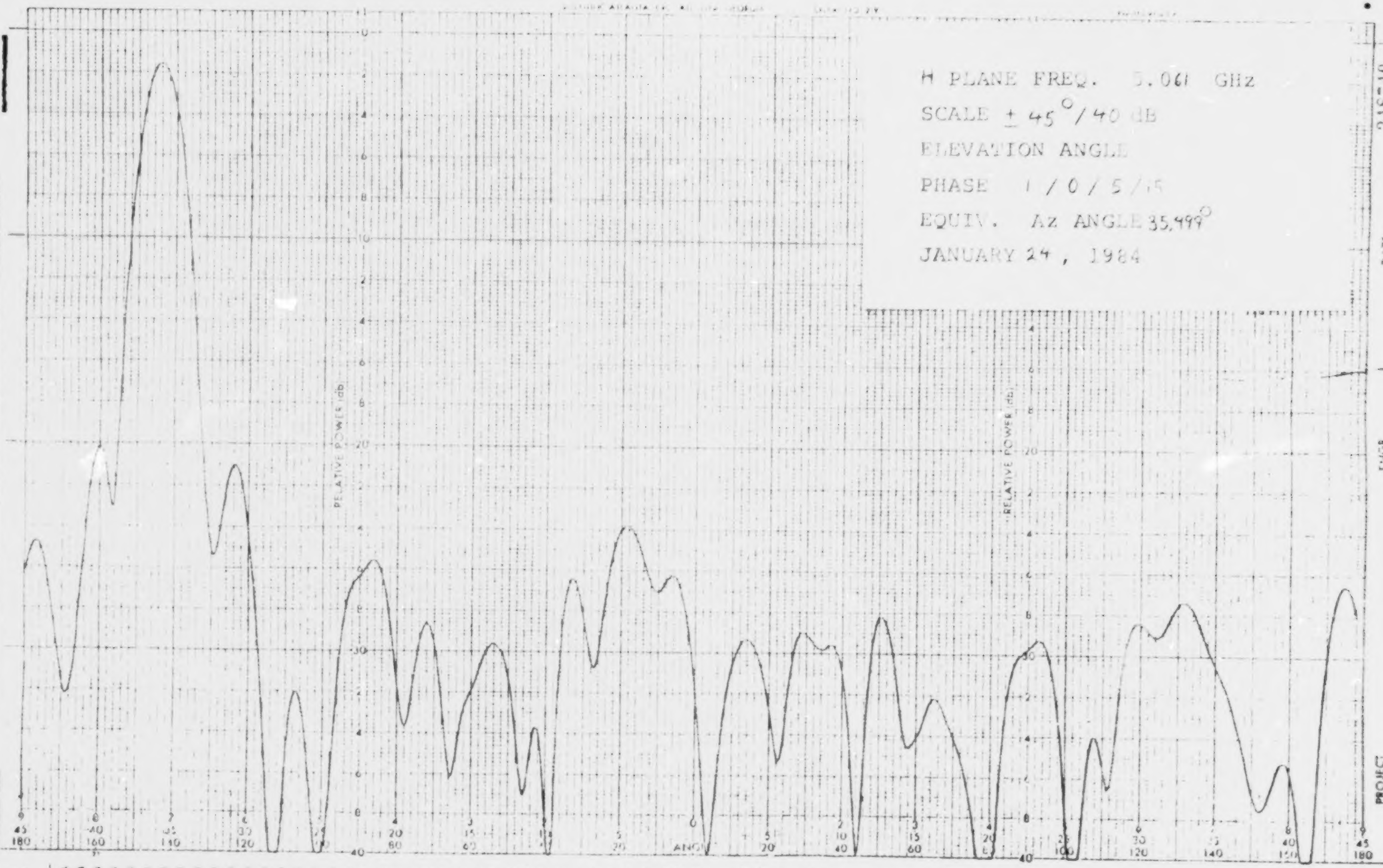
H PLANE FREQ. 5.061 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 0/1/0/14
EQUIV. Az ANGLE +0.001°
JANUARY 24, 1984



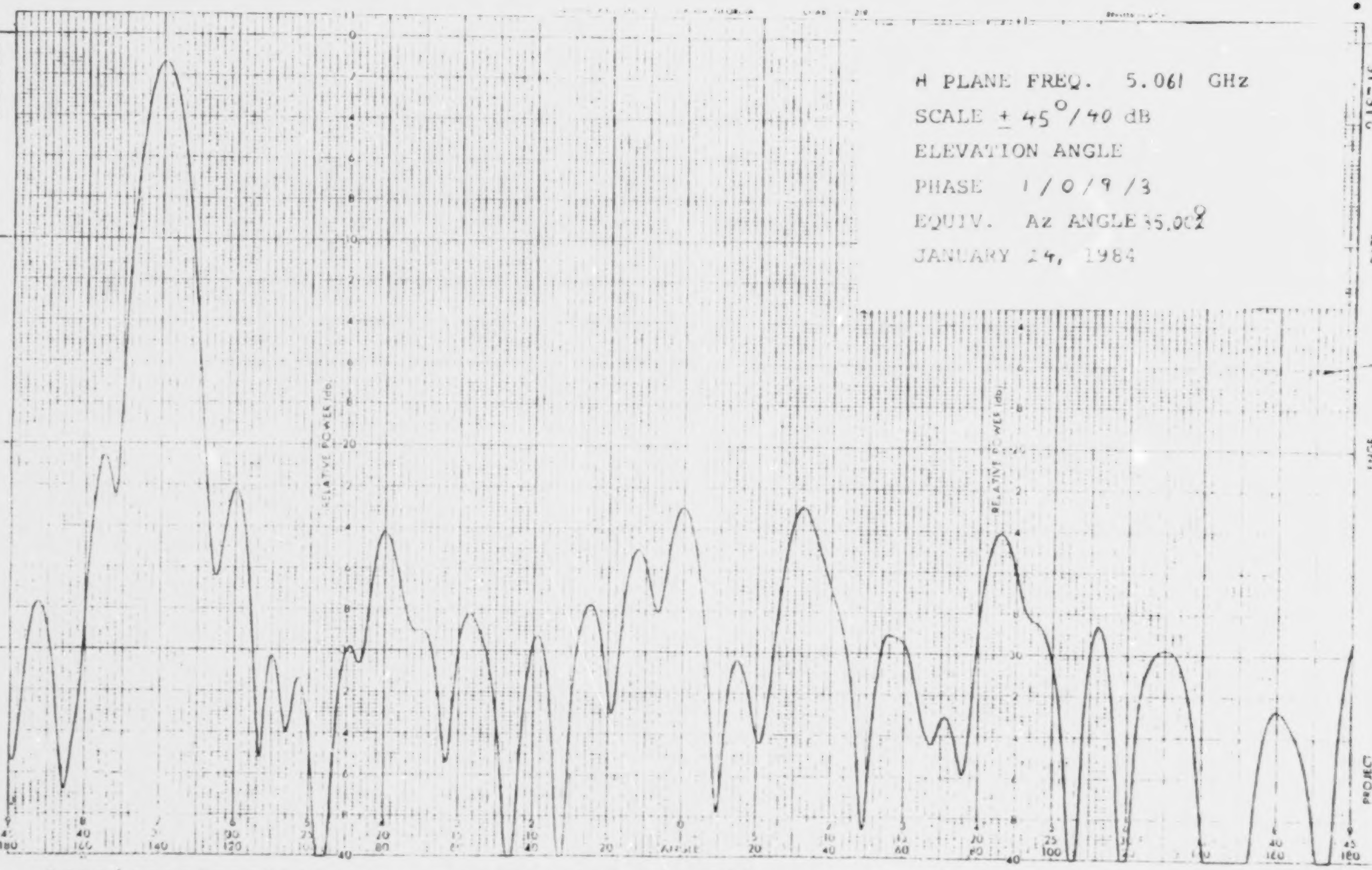
H PLANE FREQ. 5.061 GHz
SCALE ± 45°/ 40 dB
ELEVATION ANGLE
PHASE 0/1/4/0
EQUIV. Az ANGLE 38.498°
JANUARY 24, 1984

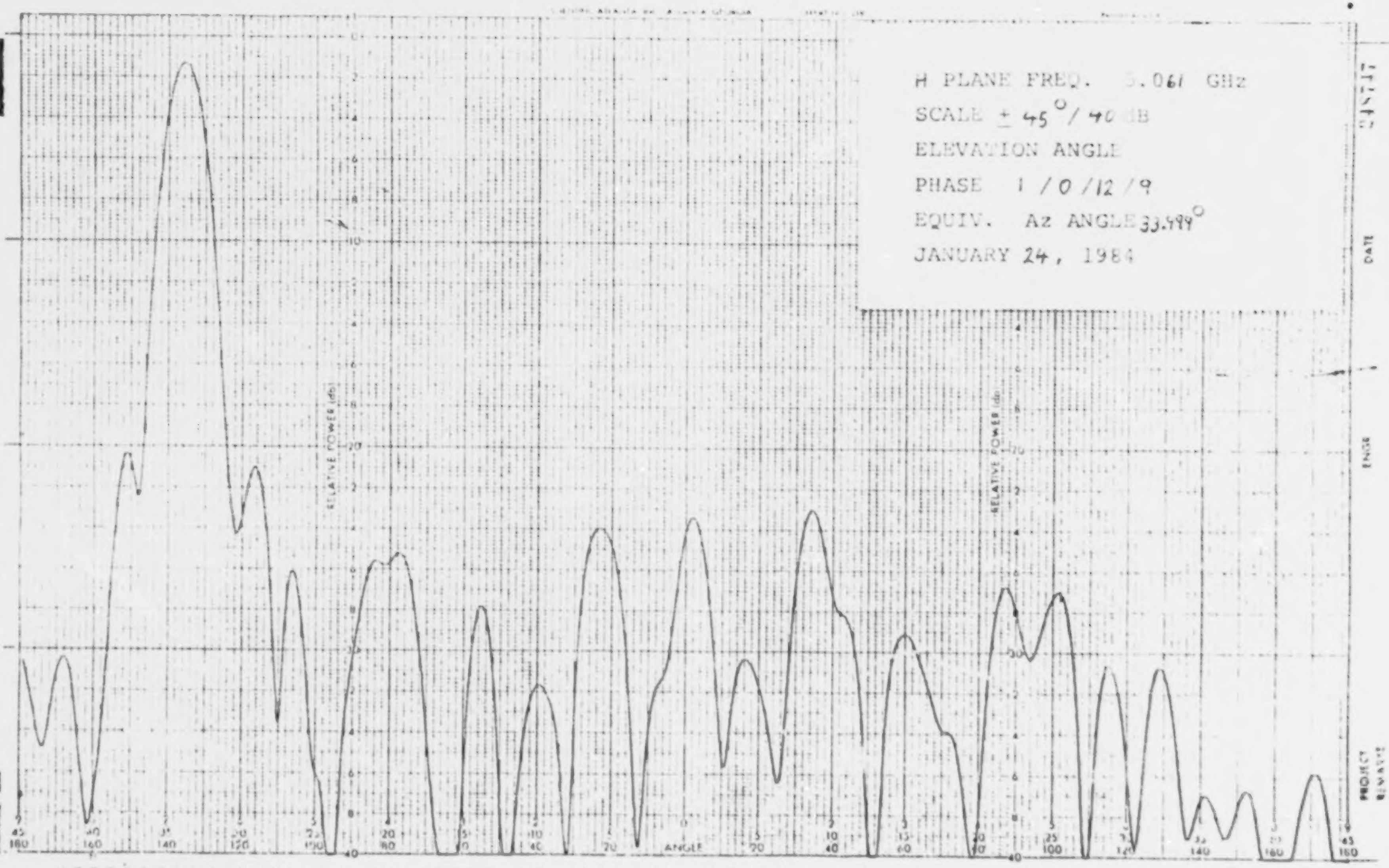

H PLANE FREQ. 5.061 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 0/1/7/1
EQUIV. Az ANGLE 37.999°
JANUARY 24, 1984


H PLANE FREQ. 5.061 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 1/0/2/11
EQUIV. Az ANGLE 37.003°
JANUARY 24, 1984
SCIENTIFIC ATLANTA INC ATLANTA GEORGIA
CHART NO 219
RELATIVE POWER (db)
ANGLE
245750
DATE
ENGR
PROJECT
REMARKS
0
10
20
30
40
45
180
140
120
100
80
60
40
20

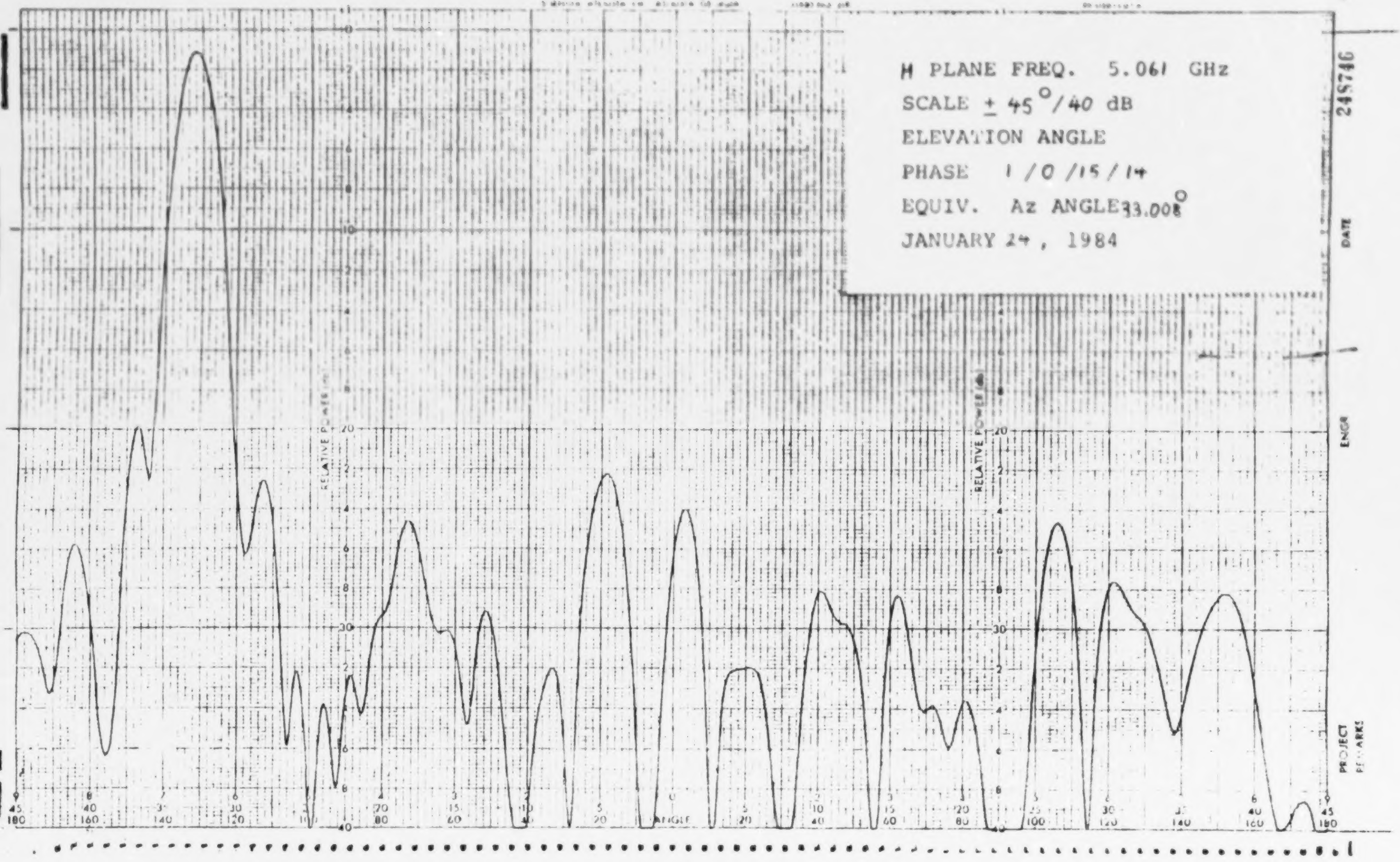


H PLANE FREQ. 5.061 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 1 / 0 / 5 / 5
EQUIV. Az ANGLE 35.999°
JANUARY 24, 1984

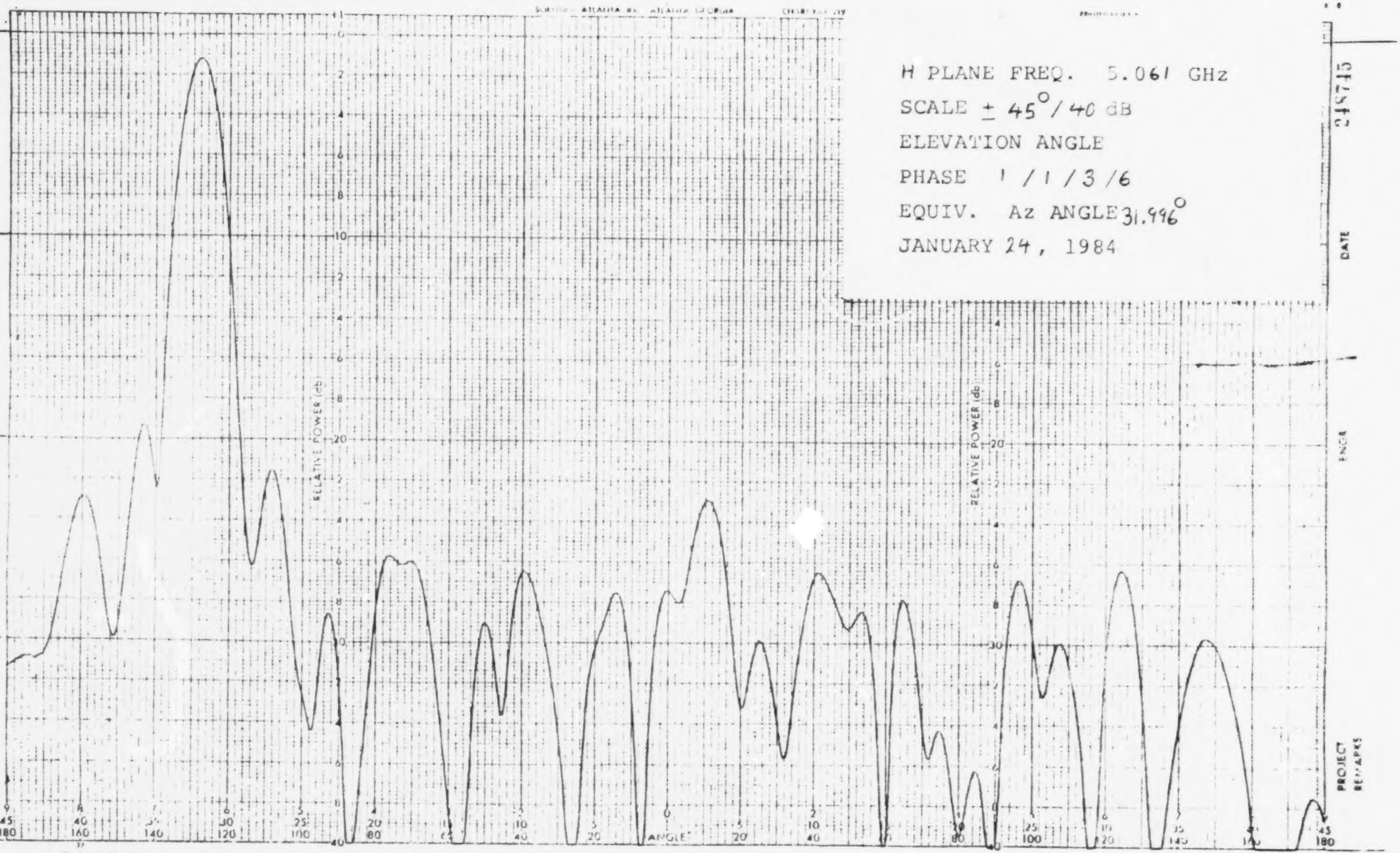

H PLANE FREQ. 5.061 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 1/0/9/3
EQUIV. Az ANGLE 35.00°
JANUARY 24, 1984
RELATIVE POWER (db)
RELATIVE POWER (db)
ANGLE
DATE
PAGE
PROJECT
245745



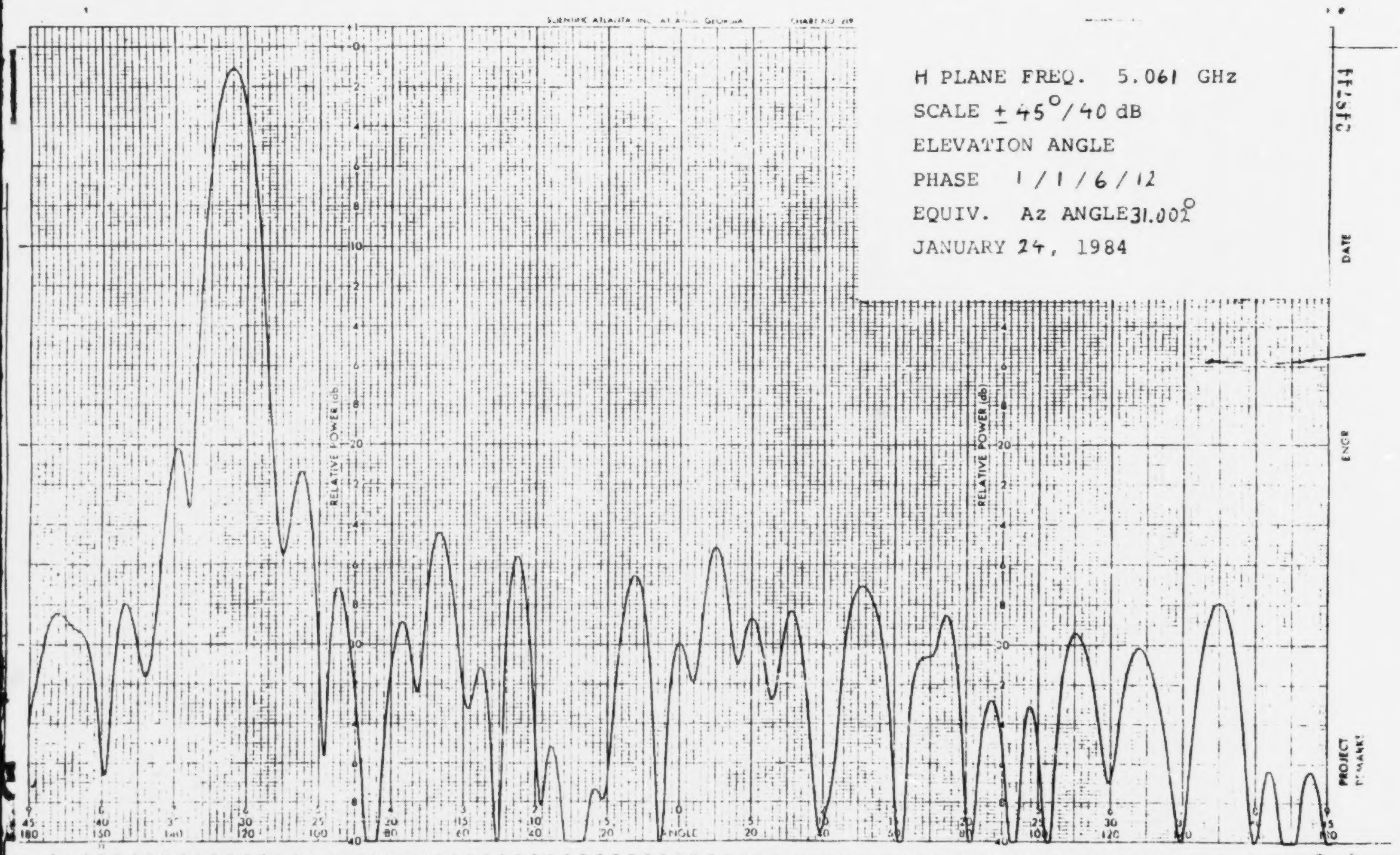
H PLANE FREQ. 5.061 GHz
SCALE ± 45°/ 40 dB
ELEVATION ANGLE
PHASE 1 / 0 /12 / 9
EQUIV. Az ANGLE 33.999°
JANUARY 24, 1984



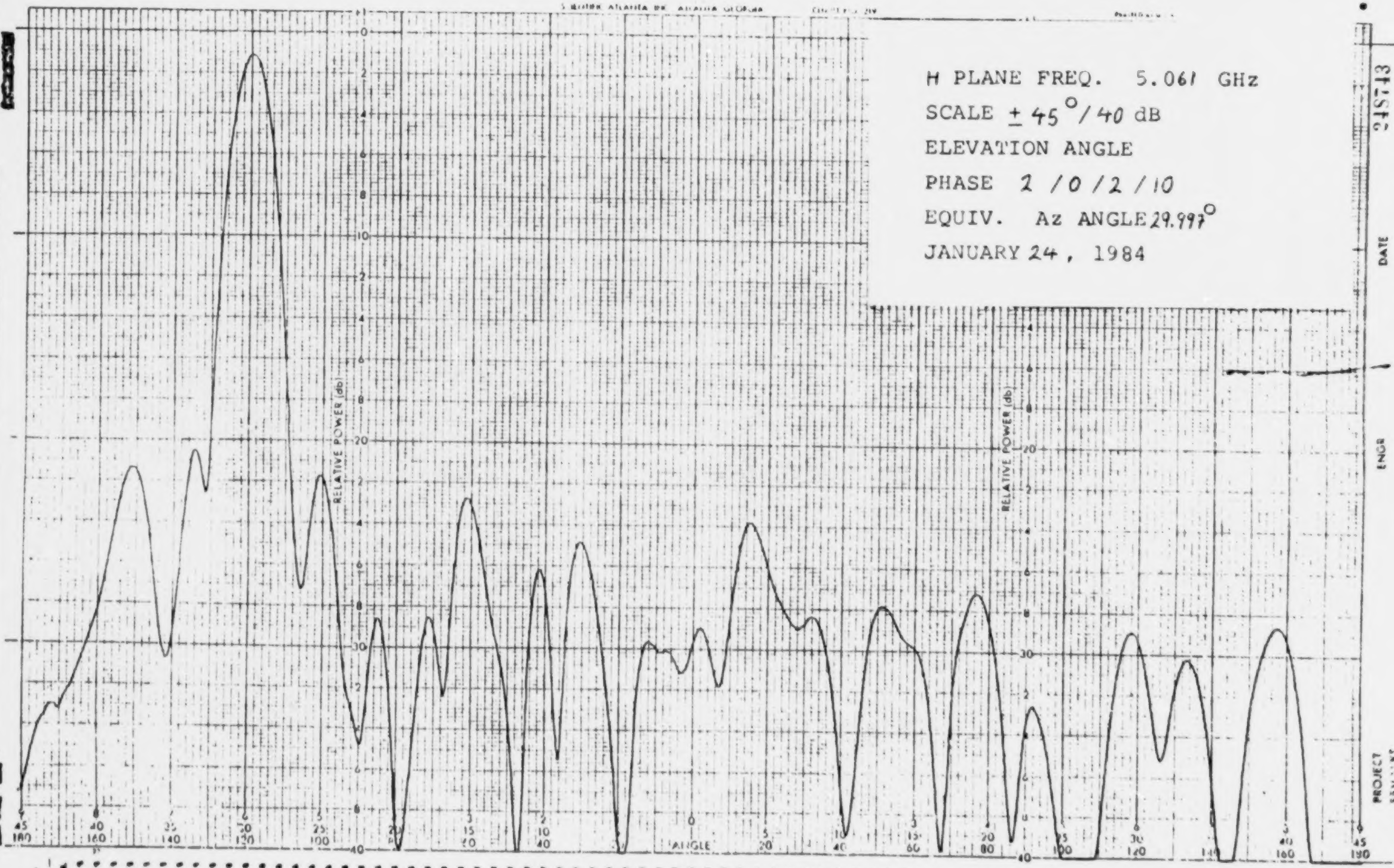
H PLANE FREQ. 5.061 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 1/0/15/14
EQUIV. Az ANGLE 33.008°
JANUARY 24, 1984



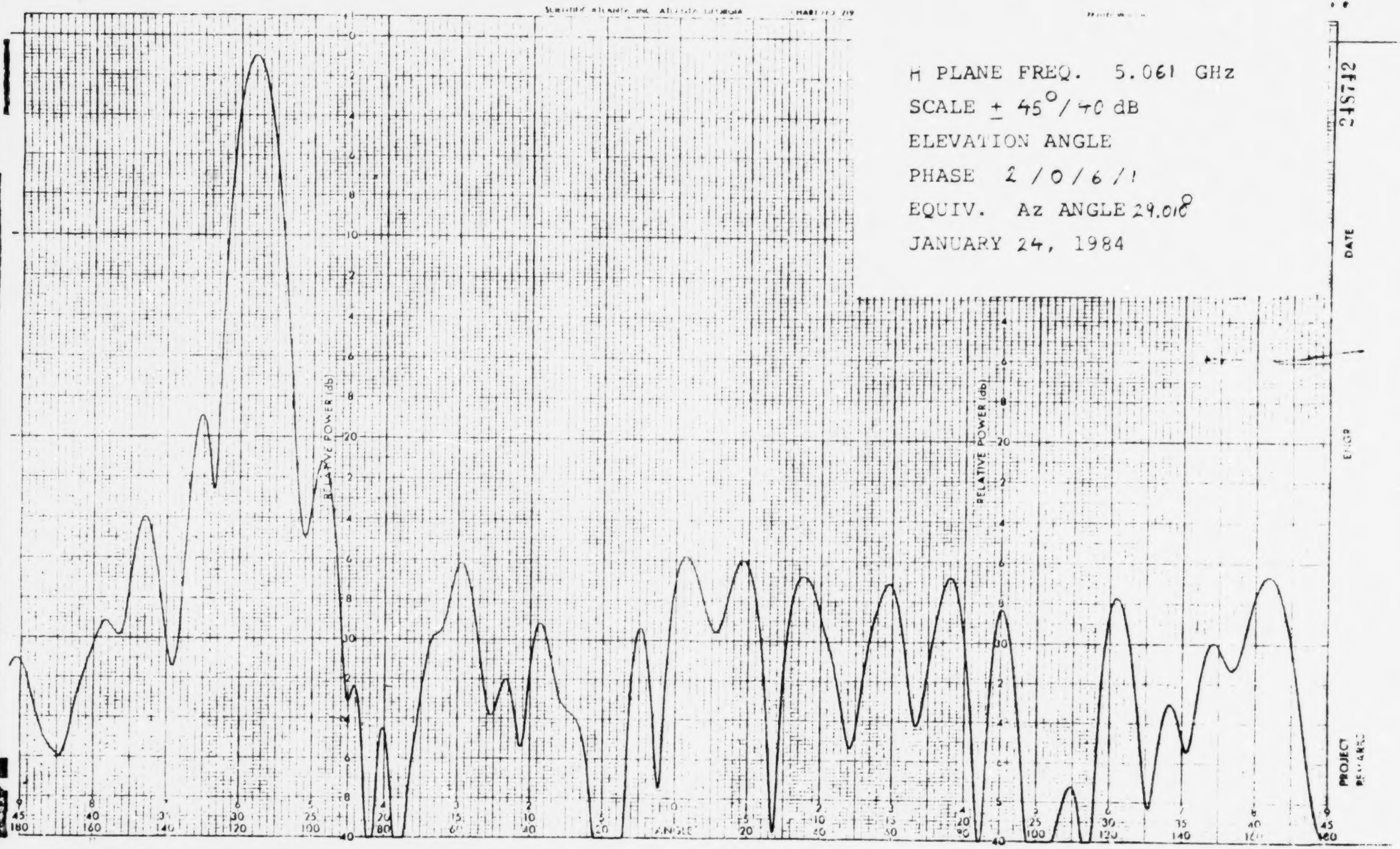
H PLANE FREQ. 5.061 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 1/1/3/6
EQUIV. Az ANGLE 31.996°
JANUARY 24, 1984



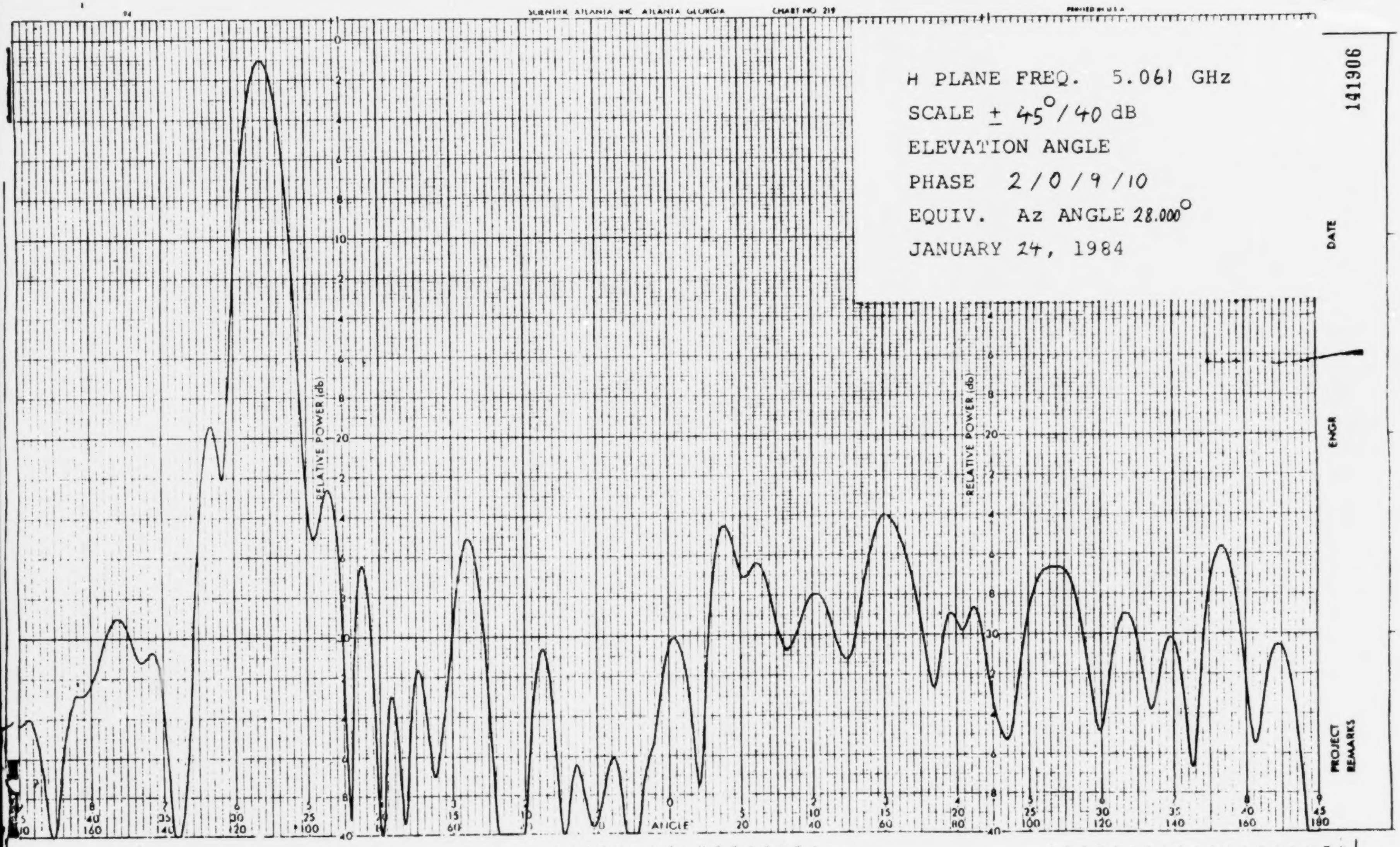
H PLANE FREQ. 5.061 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 1 / 1 / 6 / 12
EQUIV. Az ANGLE 31.002°
JANUARY 24, 1984



H PLANE FREQ. 5.061 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 2 /0 /2 /10
EQUIV. Az ANGLE 29.997°
JANUARY 24, 1984



H PLANE FREQ. 5.061 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 2/0/6/1
EQUIV. Az ANGLE 29.018
JANUARY 24, 1984



H PLANE FREQ. 5.061 GHz

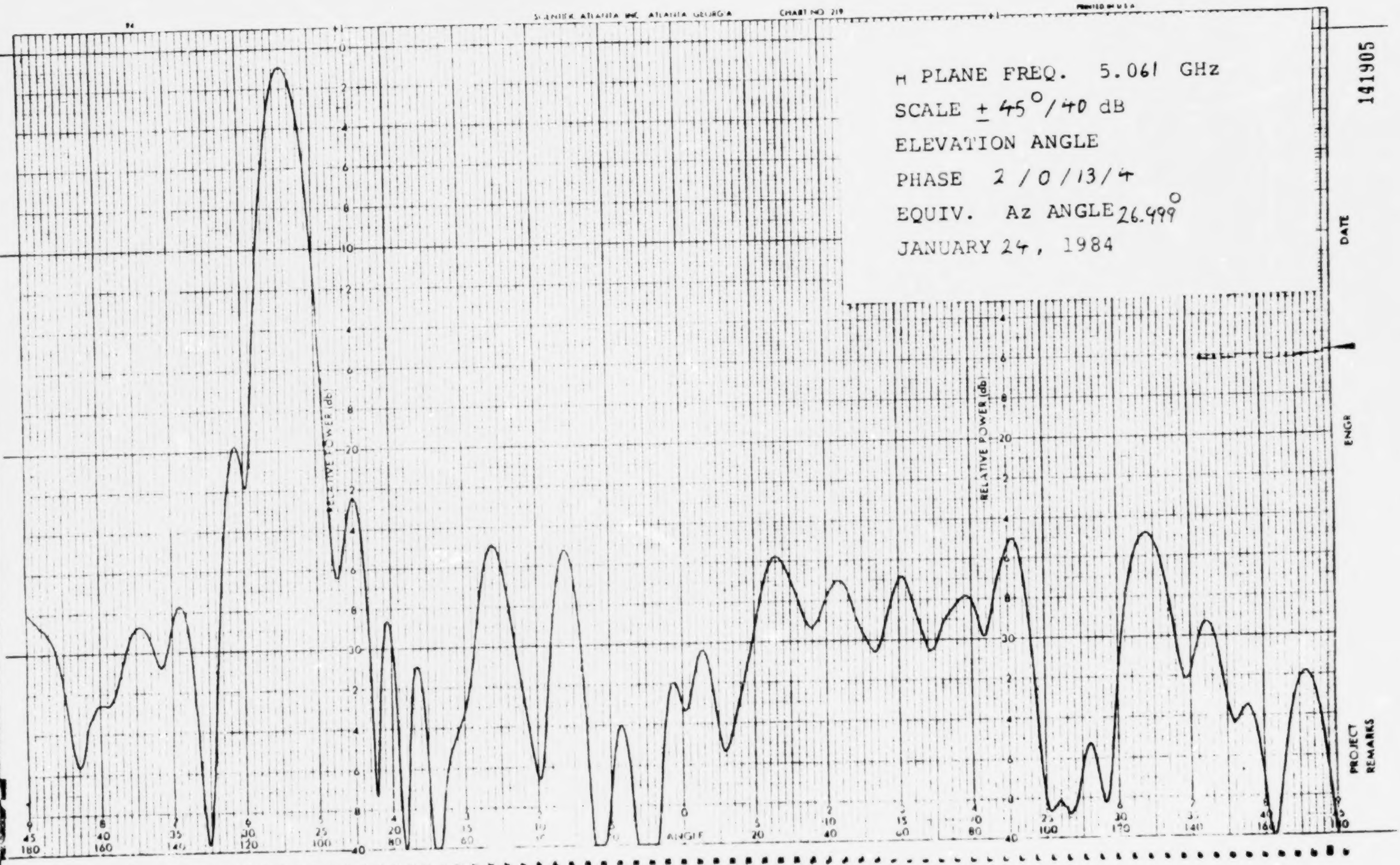
SCALE ± 45°/40 dB

ELEVATION ANGLE

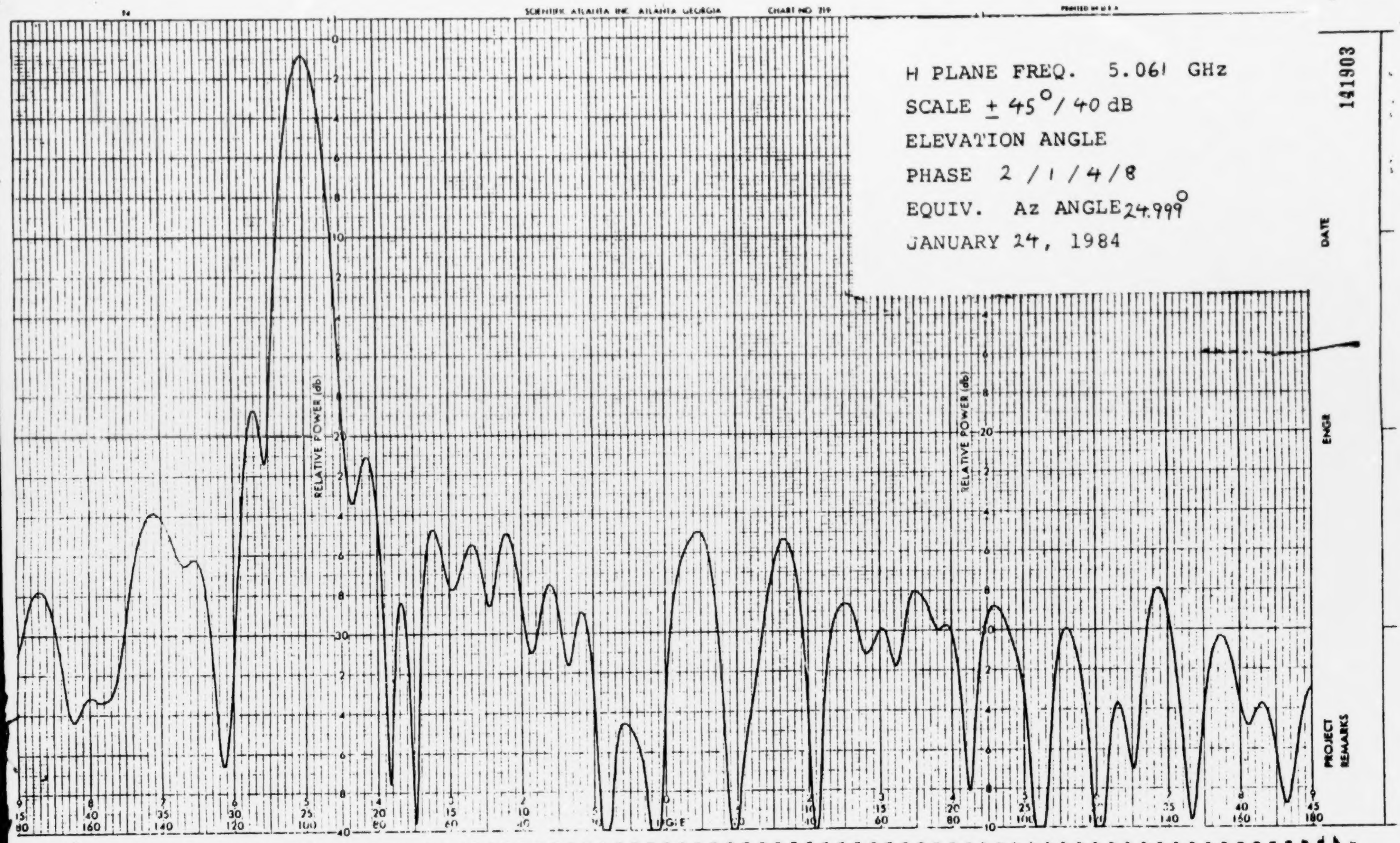
PHASE 2/0/9/10

EQUIV. Az ANGLE 28.000°

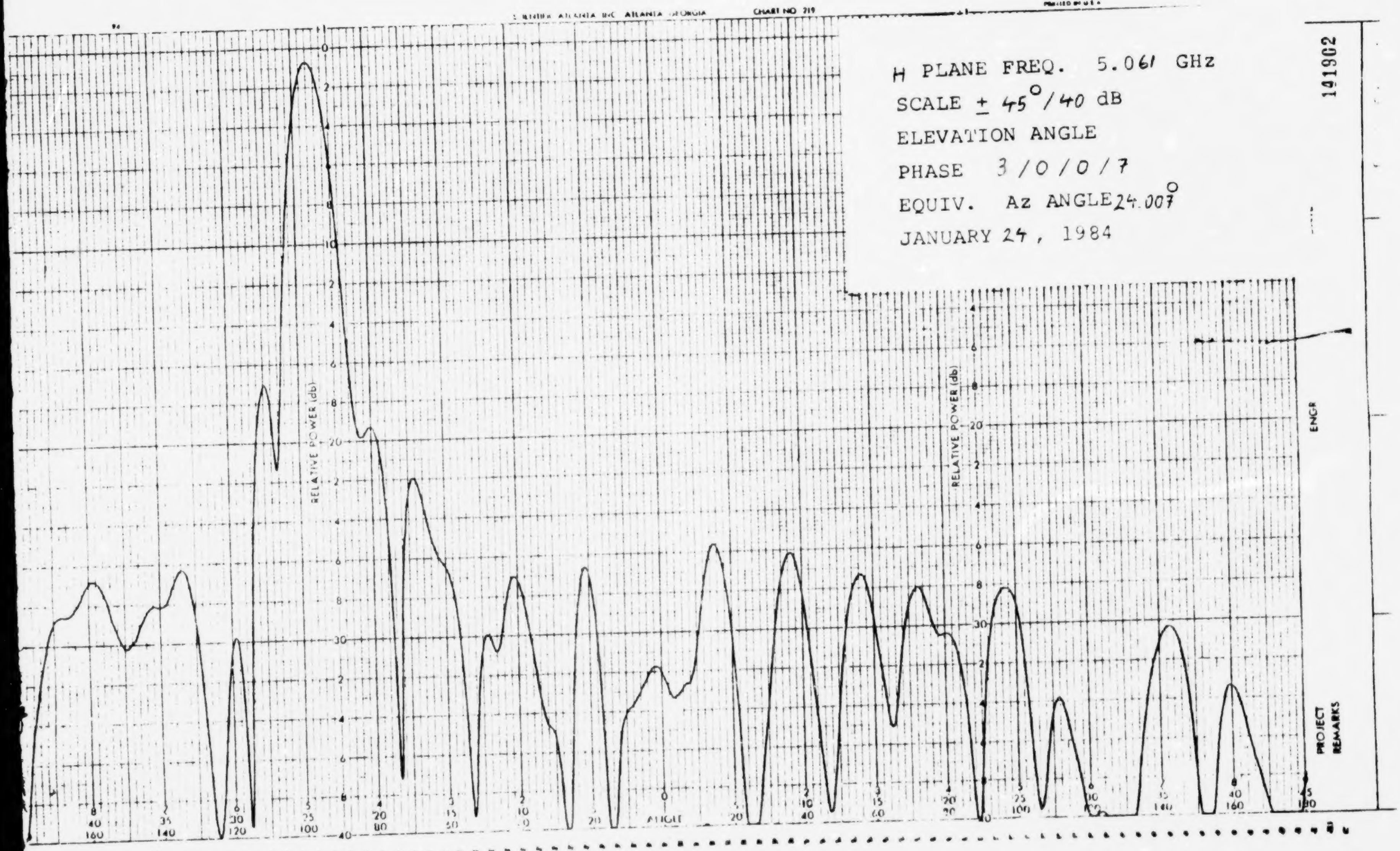
JANUARY 24, 1984



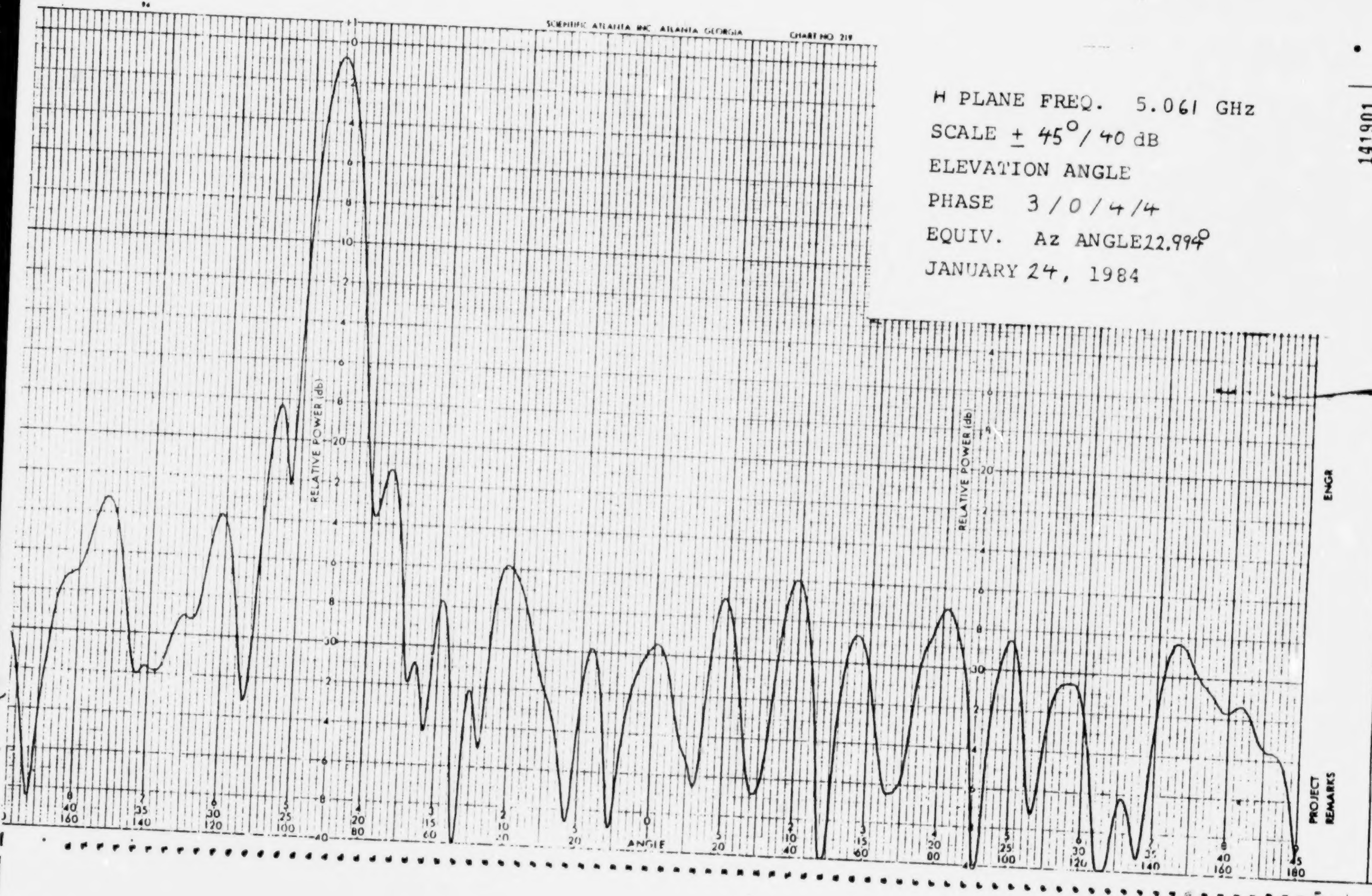
H PLANE FREQ. 5.061 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 2/0/13/4
EQUIV. Az ANGLE 26.999°
JANUARY 24, 1984



H PLANE FREQ. 5.061 GHz
SCALE ± 45°/ 40 dB
ELEVATION ANGLE
PHASE 2 / 1 / 4 / 8
EQUIV. Az ANGLE 24.999°
JANUARY 24, 1984

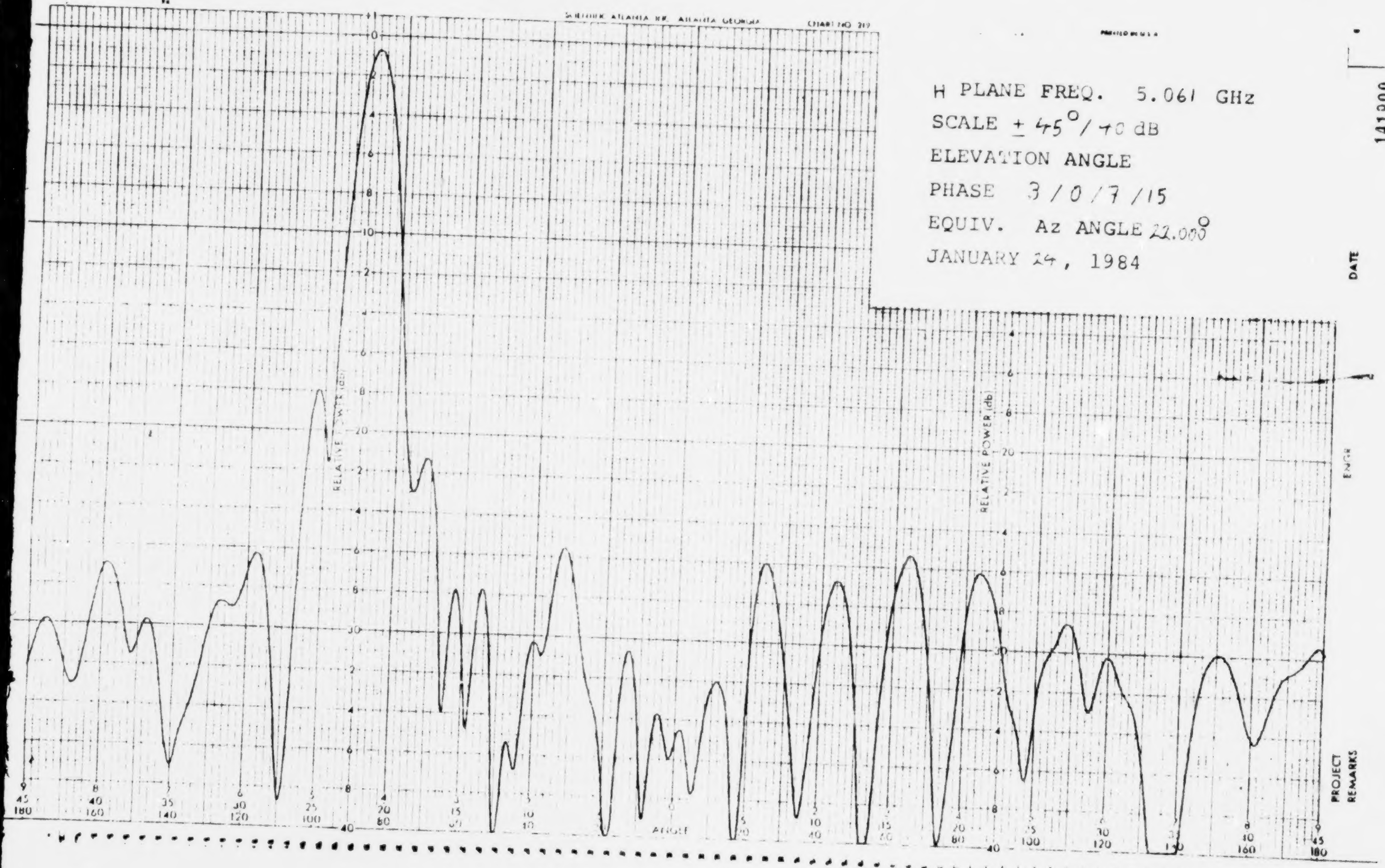


H PLANE FREQ. 5.061 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 3/0/0/7
EQUIV. Az ANGLE 24.007°
JANUARY 24, 1984



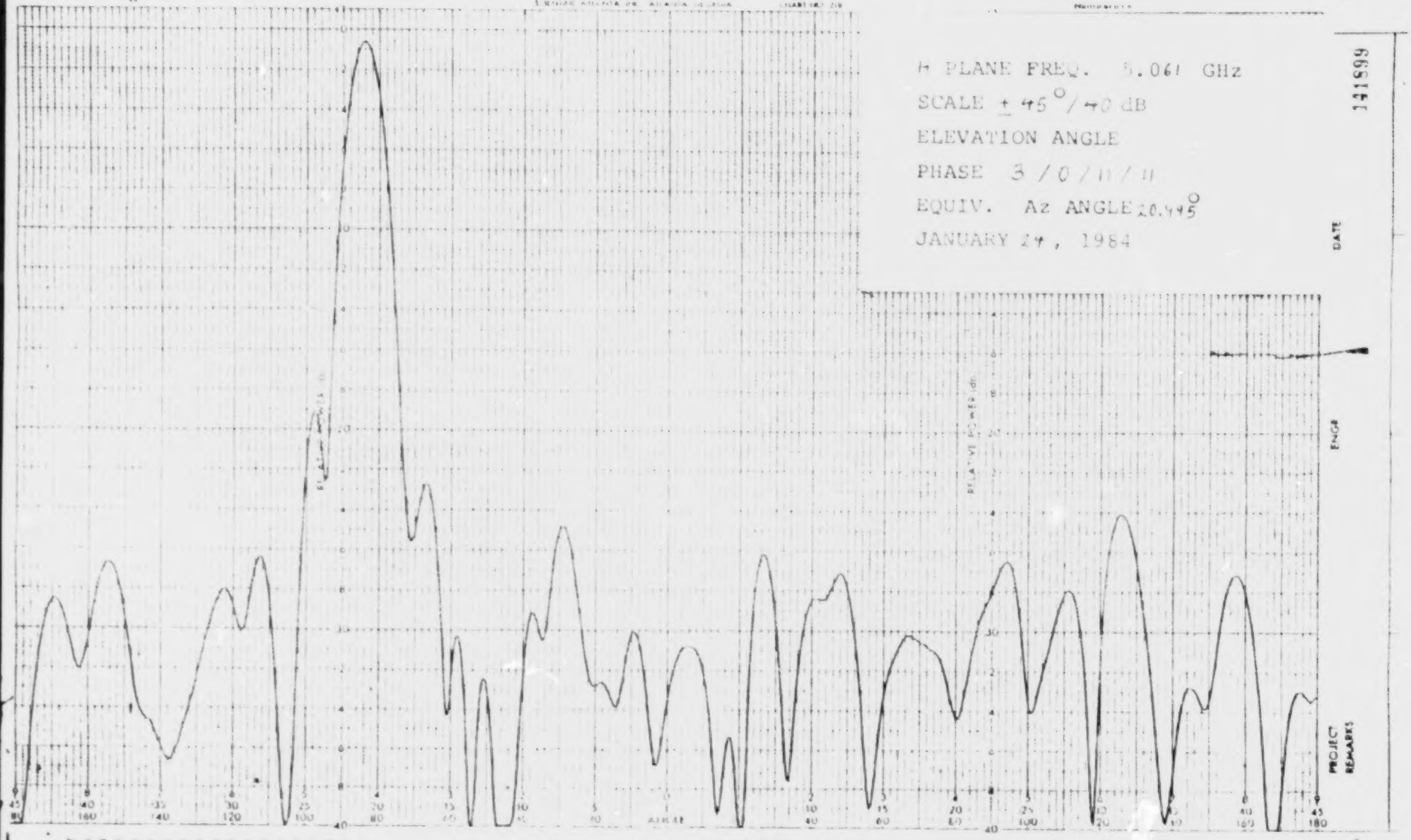
H PLANE FREQ. 5.061 GHz
SCALE ± 45°/ 40 dB
ELEVATION ANGLE
PHASE 3 / 0 / 4 / 4
EQUIV. Az ANGLE 22.994°
JANUARY 24, 1984

141901



H PLANE FREQ. 5.061 GHz
SCALE ± 45°/ 40 dB
ELEVATION ANGLE
PHASE 3/0/7/15
EQUIV. Az ANGLE 22.000°
JANUARY 24, 1984

141900



H PLANE FREQ. 5.061 GHz

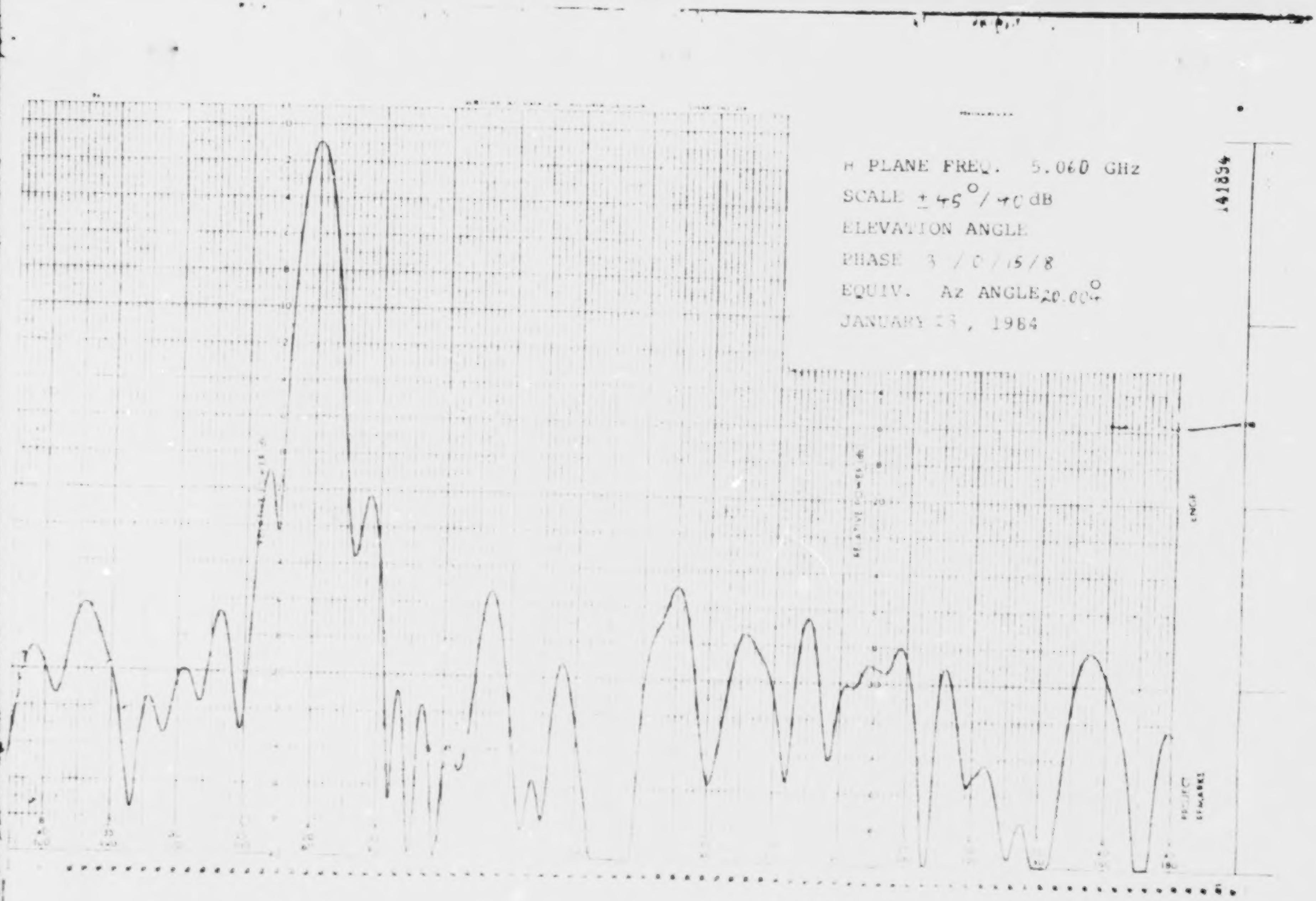
SCALE ± 45°/40 dB

ELEVATION ANGLE

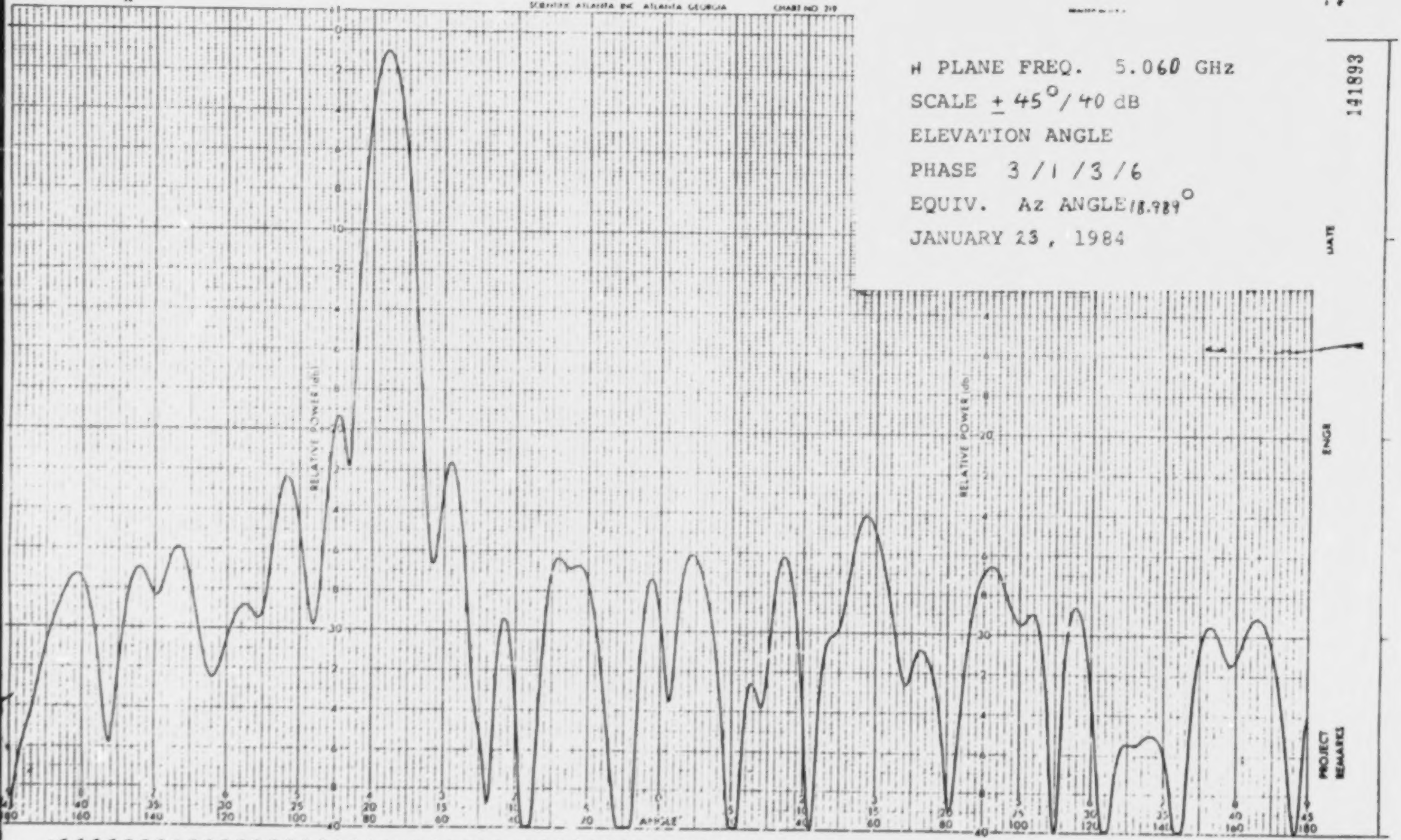
PHASE 3/0/0/0

EQUIV. Az ANGLE 20.445°

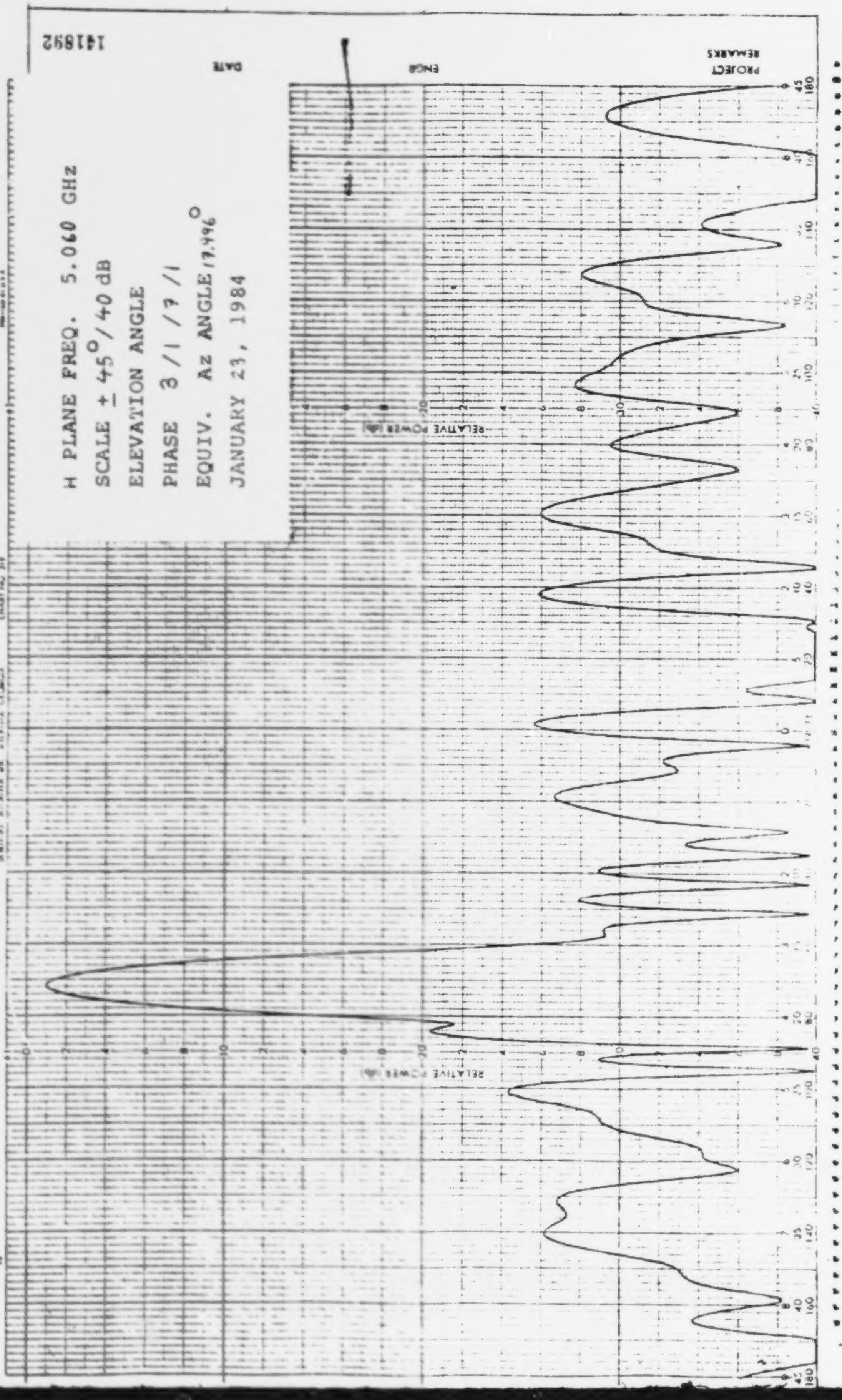
JANUARY 24, 1984



H PLANE FREQ. 5.060 GHz
SCALE ± 45°/ 40 dB
ELEVATION ANGLE
PHASE 3 / 0 / 15 / 8
EQUIV. Az ANGLE 20.00°
JANUARY 23, 1984



H PLANE FREQ. 5.060 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 3/1/3/6
EQUIV. Az ANGLE 18.989°
JANUARY 23, 1984



H PLANE FREQ. 5.060 GHz

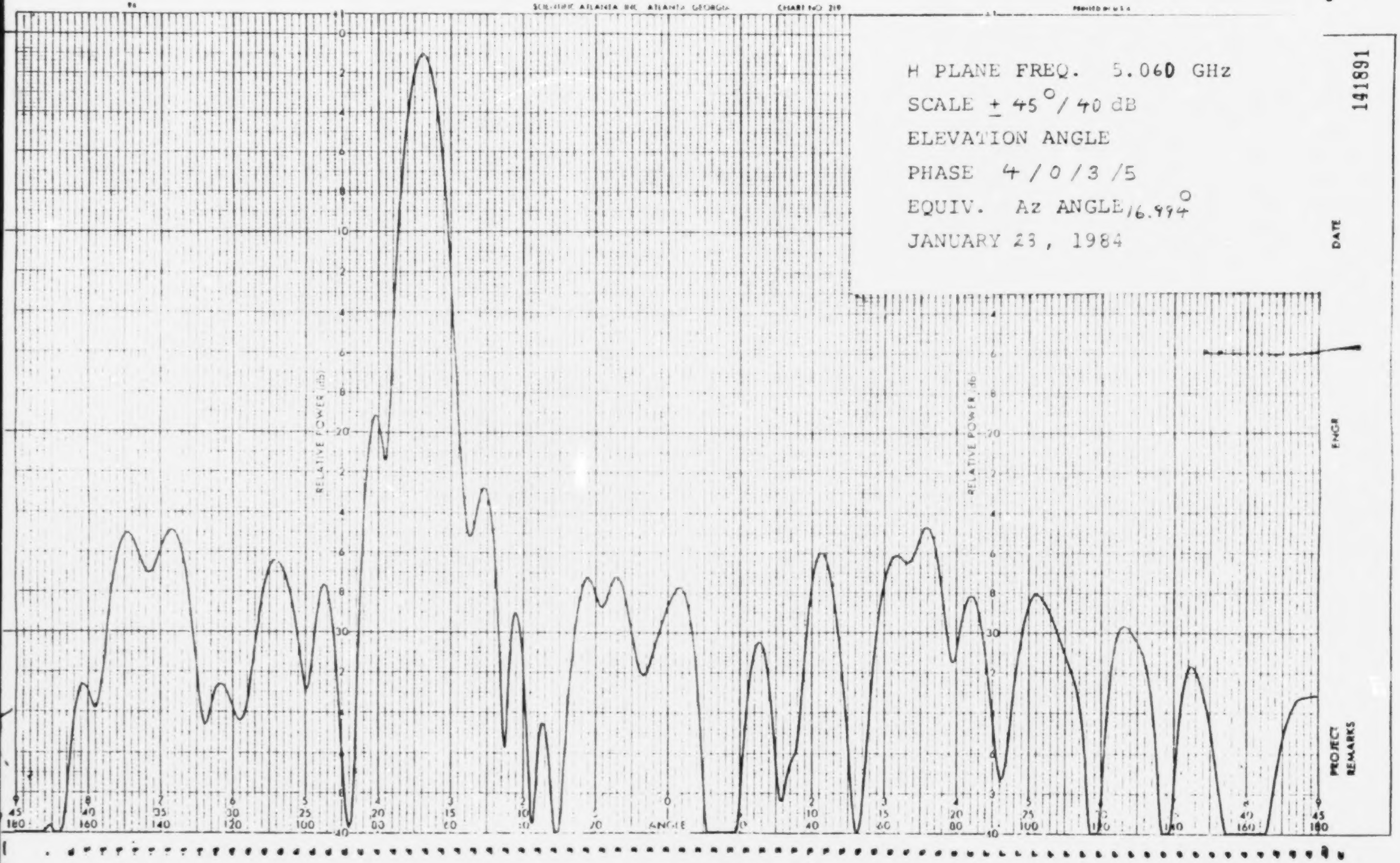
SCALE ± 45°/40 dB

ELEVATION ANGLE

PHASE 3/1/7/1

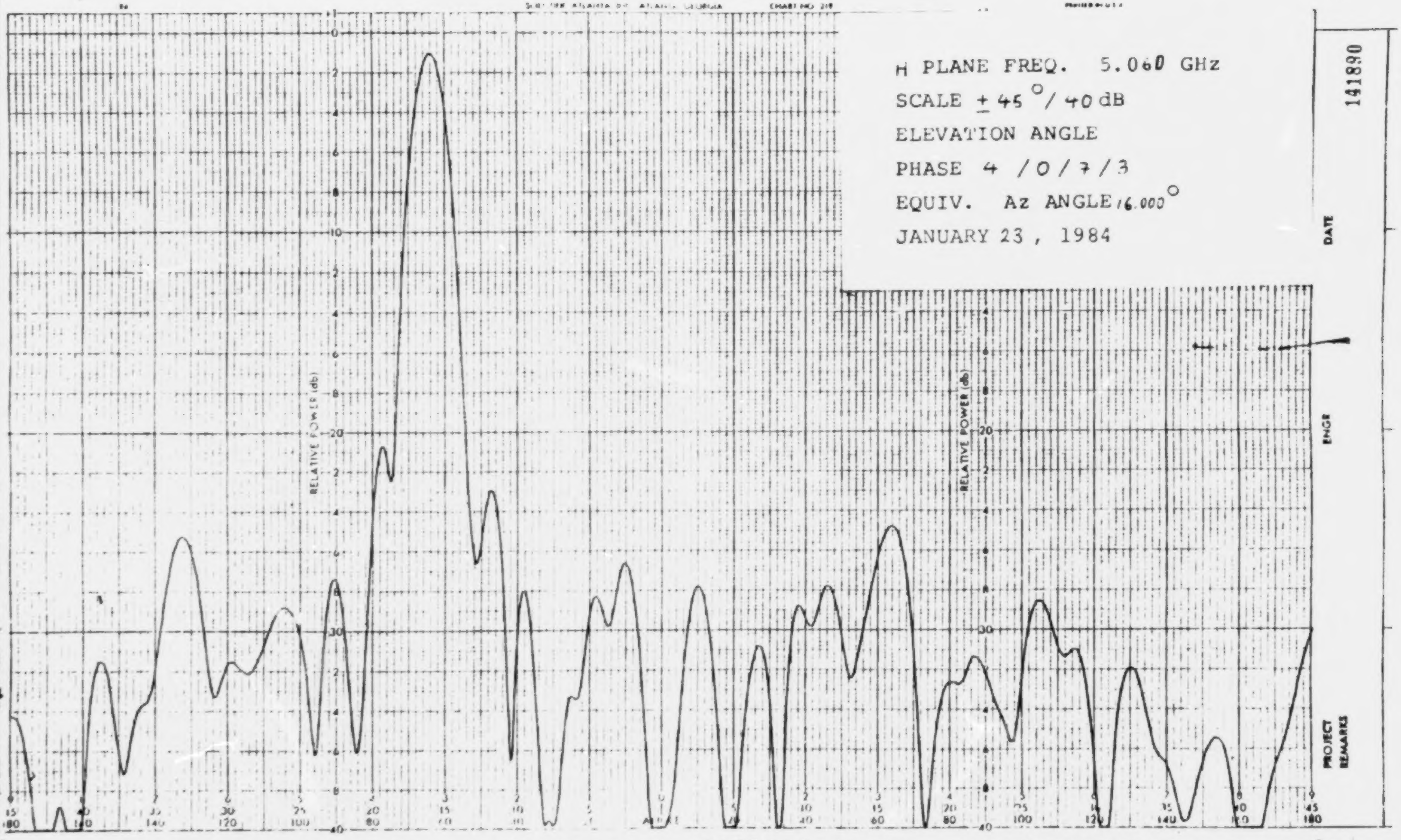
EQUIV. Az ANGLE 17.996°

JANUARY 23, 1984

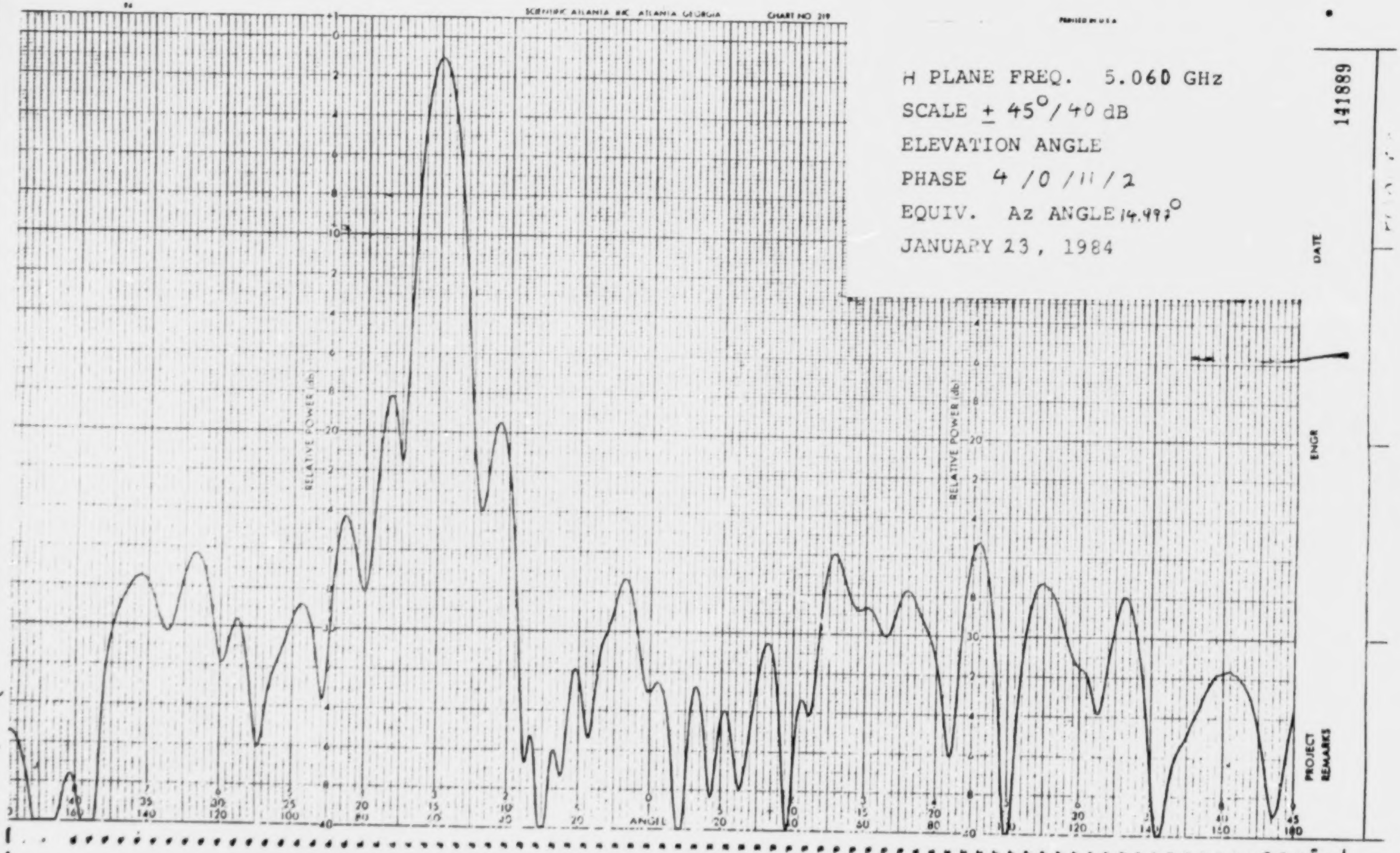


H PLANE FREQ. 5.060 GHz
SCALE ± 45°/ 40 dB
ELEVATION ANGLE
PHASE 4 / 0 / 3 / 5
EQUIV. Az ANGLE 16.994°
JANUARY 23 , 1984

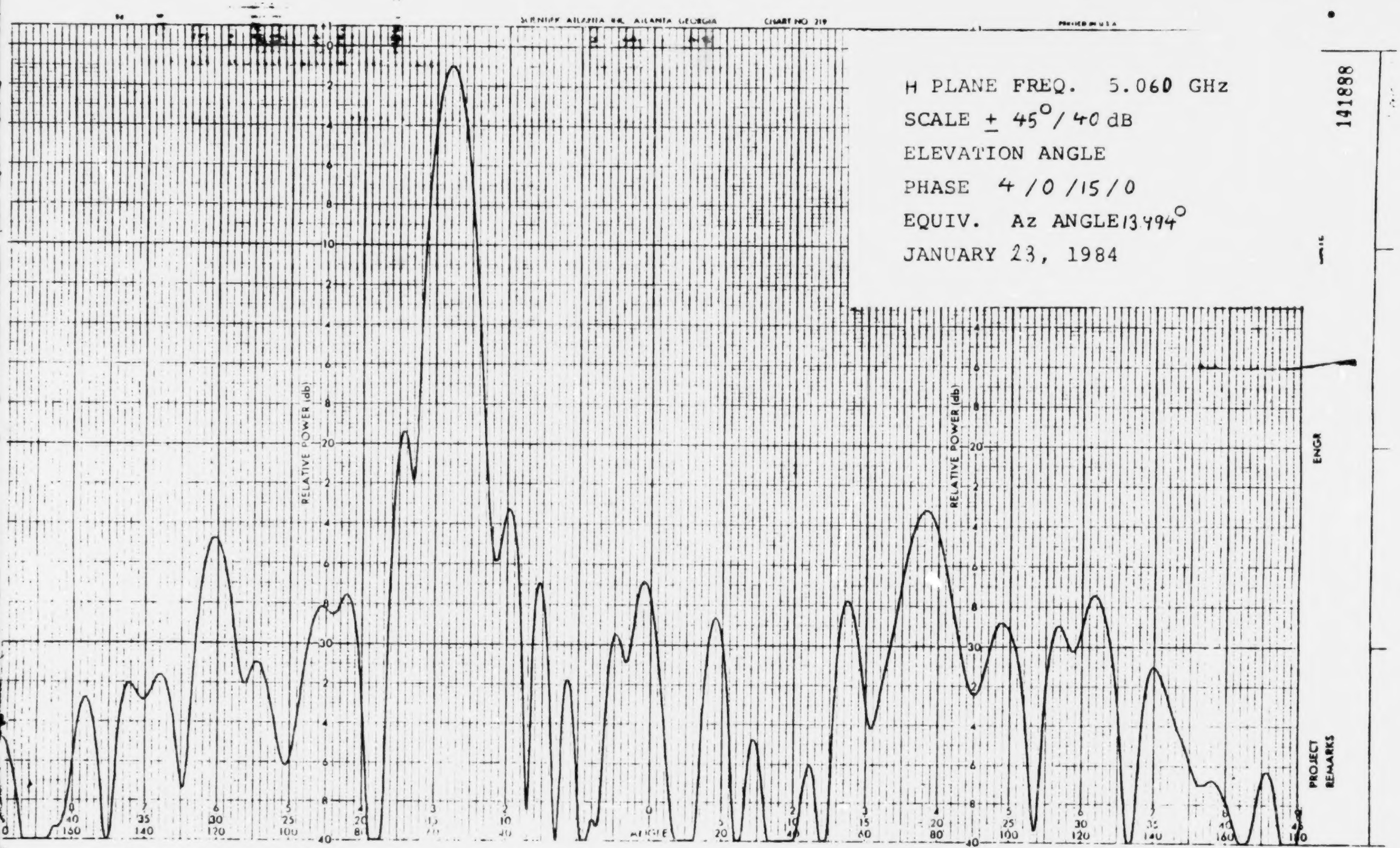
141891



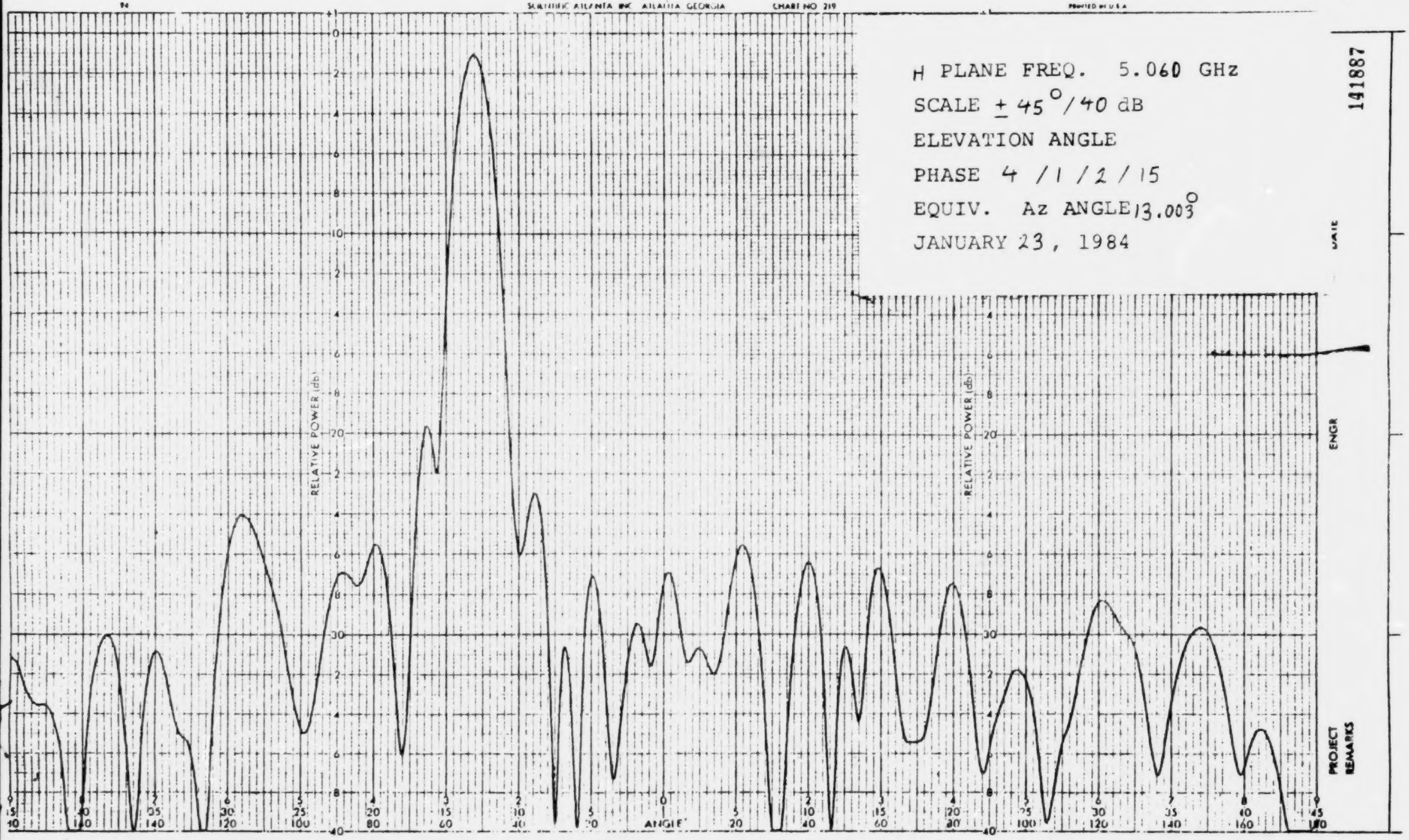
H PLANE FREQ. 5.060 GHz
SCALE ± 45°/ 40 dB
ELEVATION ANGLE
PHASE 4 /0/7/3
EQUIV. Az ANGLE 16.000°
JANUARY 23 , 1984



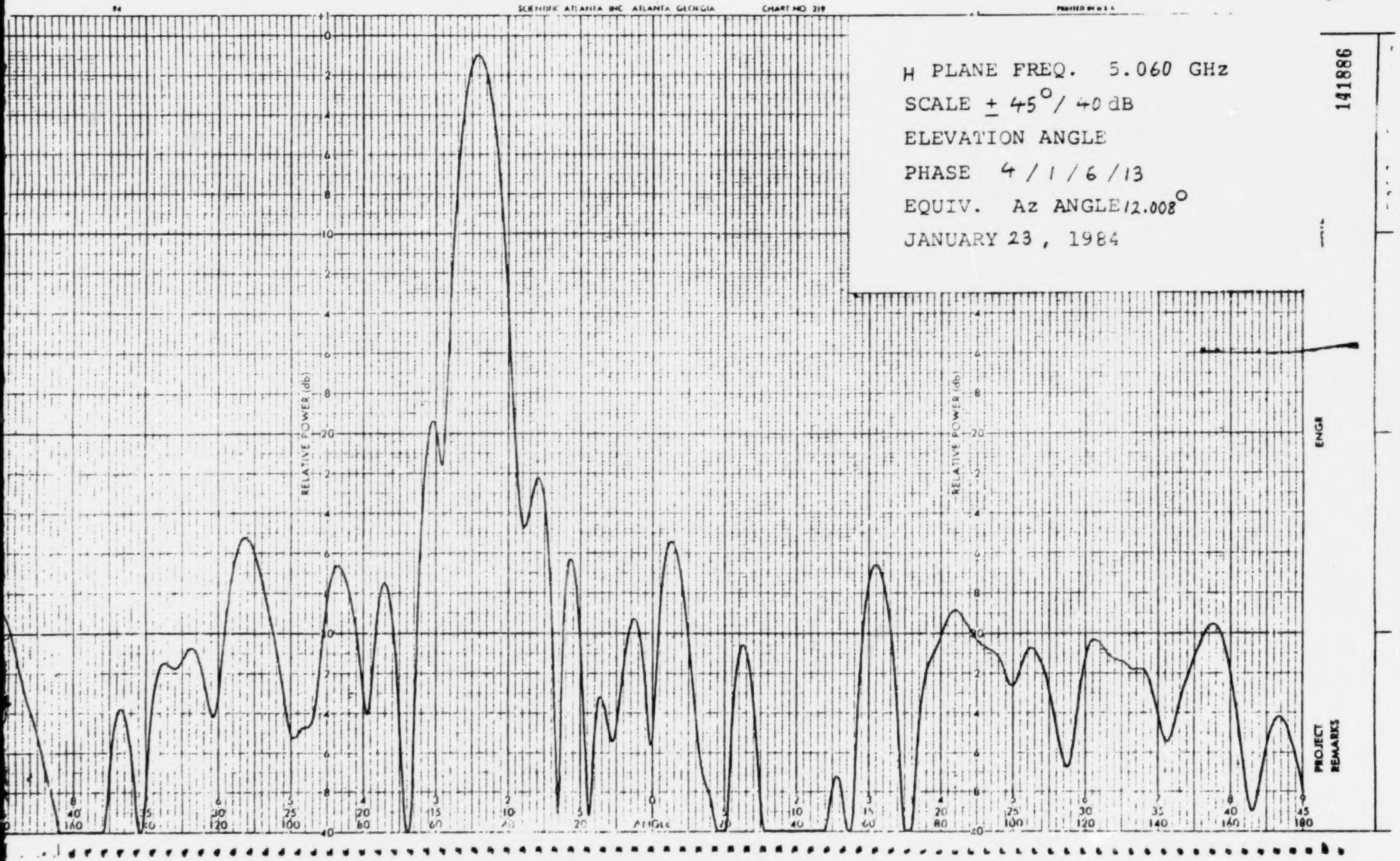
H PLANE FREQ. 5.060 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 4 /0 /11 /2
EQUIV. Az ANGLE 14.997°
JANUARY 23 , 1984



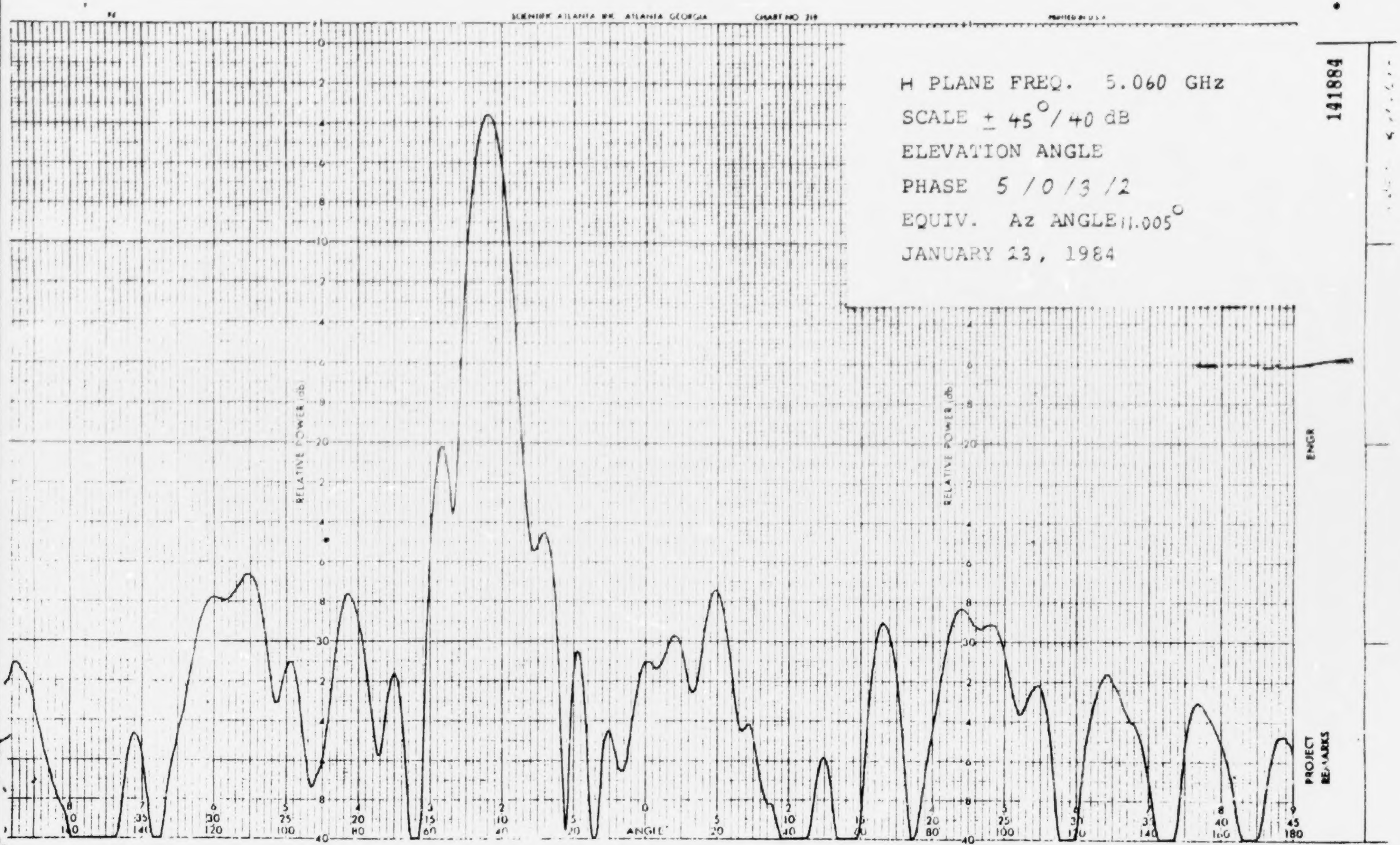
H PLANE FREQ. 5.060 GHz
SCALE ± 45°/ 40 dB
ELEVATION ANGLE
PHASE 4 /0 /15/0
EQUIV. Az ANGLE 13.494°
JANUARY 23, 1984



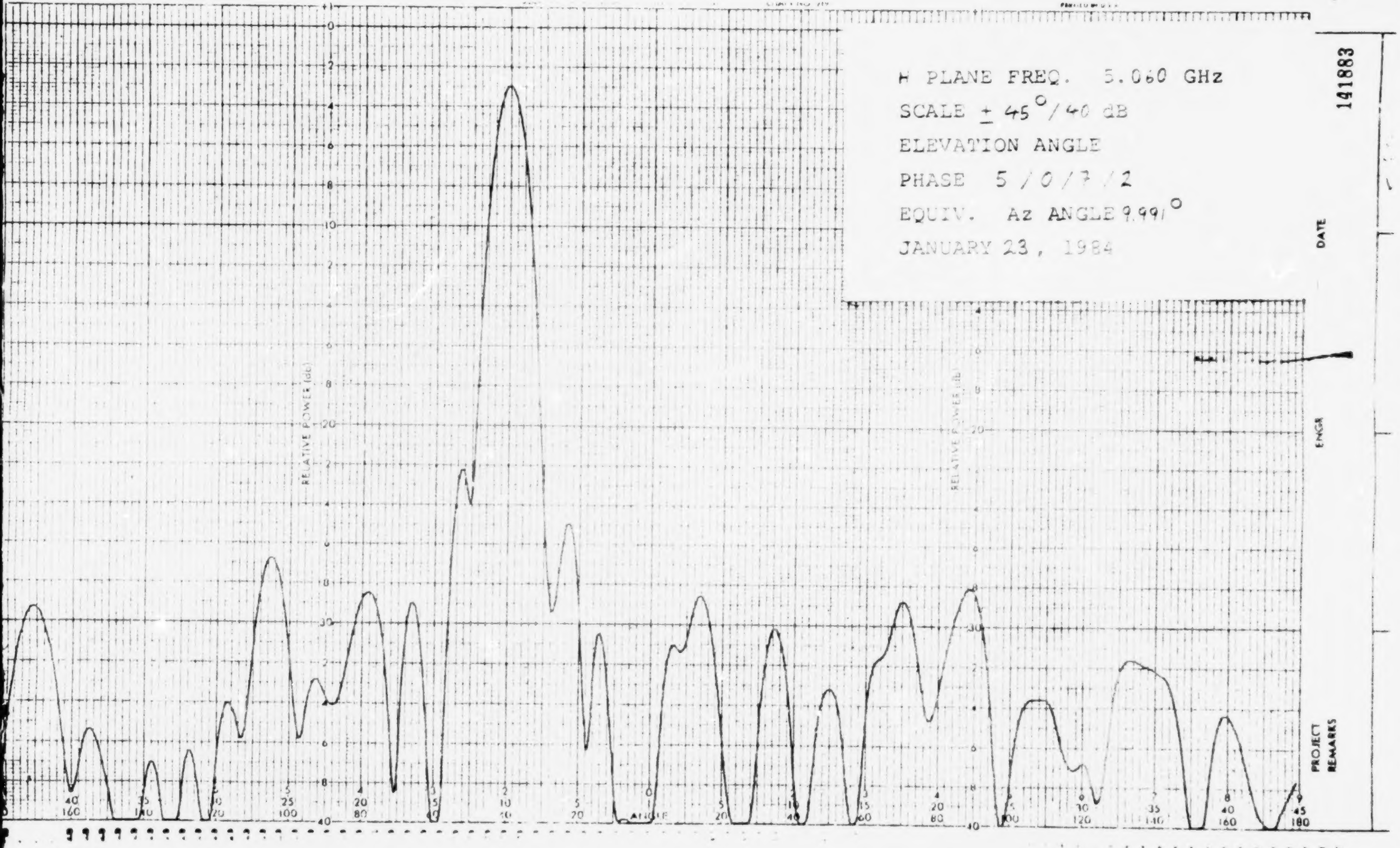
H PLANE FREQ. 5.060 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 4 / 1 / 2 / 15
EQUIV. Az ANGLE 13.003°
JANUARY 23, 1984



H PLANE FREQ. 5.060 GHz
SCALE ± 45°/ 40 dB
ELEVATION ANGLE
PHASE 4 / 1 / 6 / 13
EQUIV. Az ANGLE 12.008°
JANUARY 23 , 1984



H PLANE FREQ. 5.060 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 5 /0 /3 /2
EQUIV. Az ANGLE 11.005°
JANUARY 23, 1984



H PLANE FREQ. 5.060 GHz

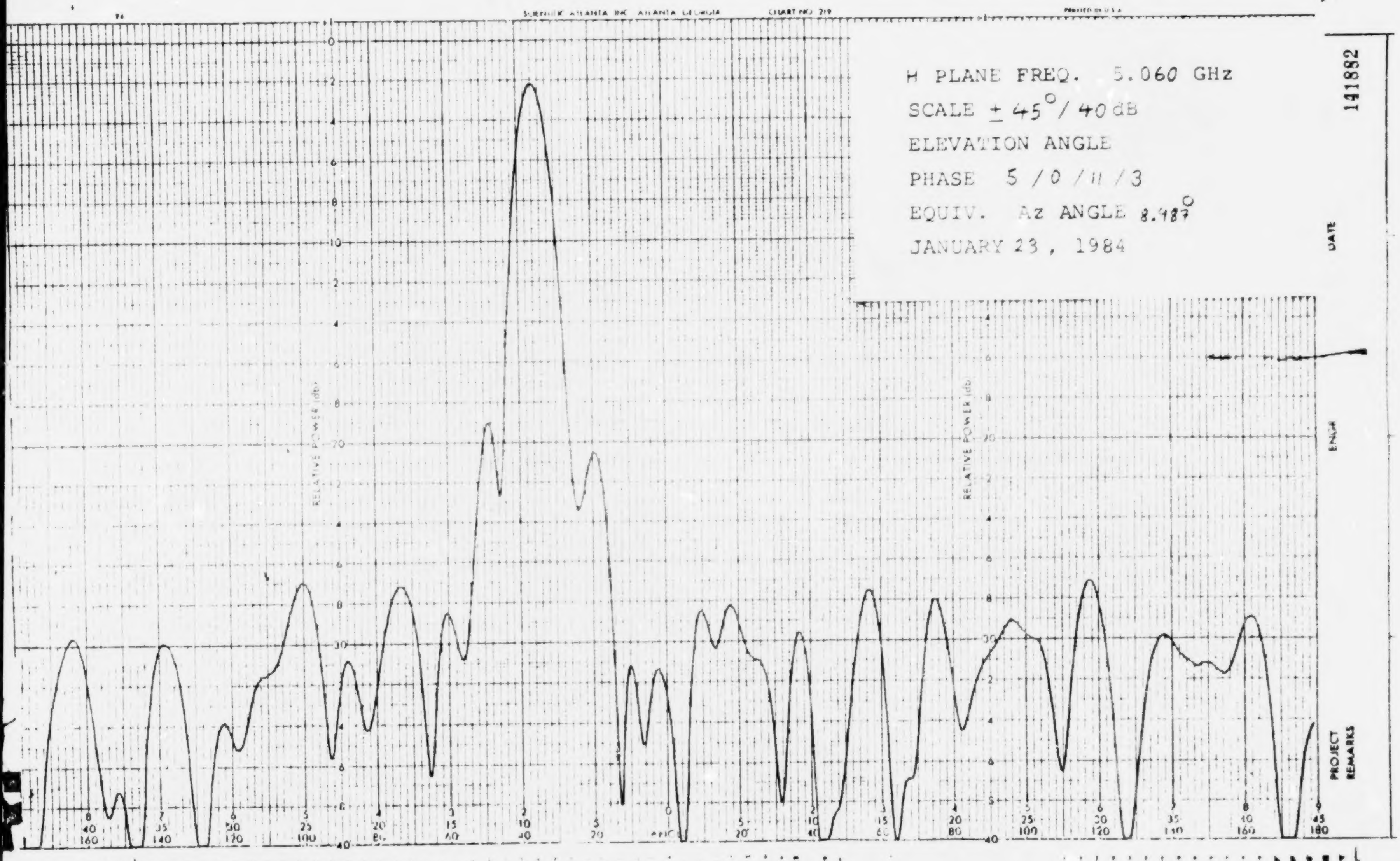
SCALE ± 45°/40 dB

ELEVATION ANGLE

PHASE 5 / 0 / 7 / 2

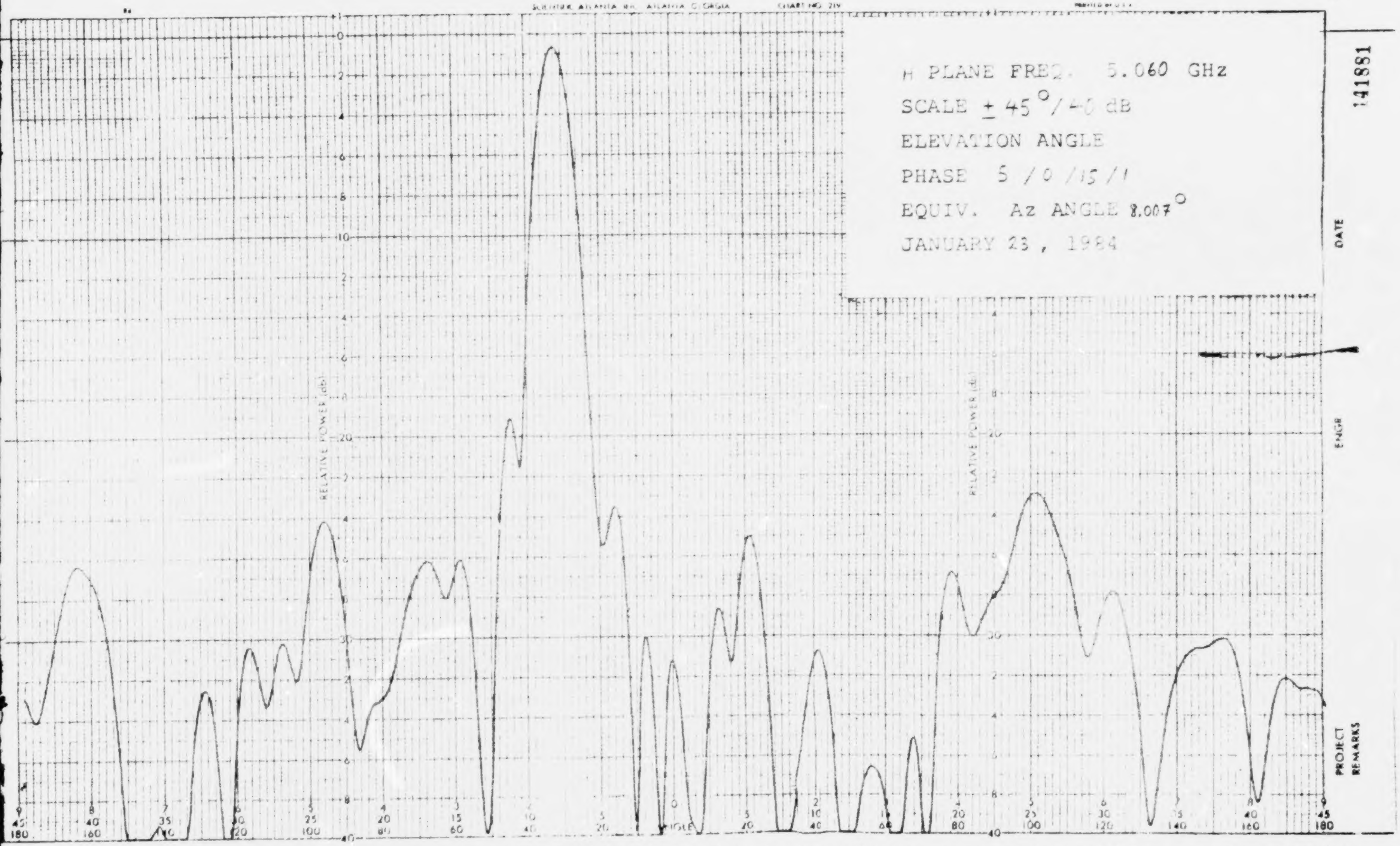
EQUIV. Az ANGLE 9.991°

JANUARY 23, 1984

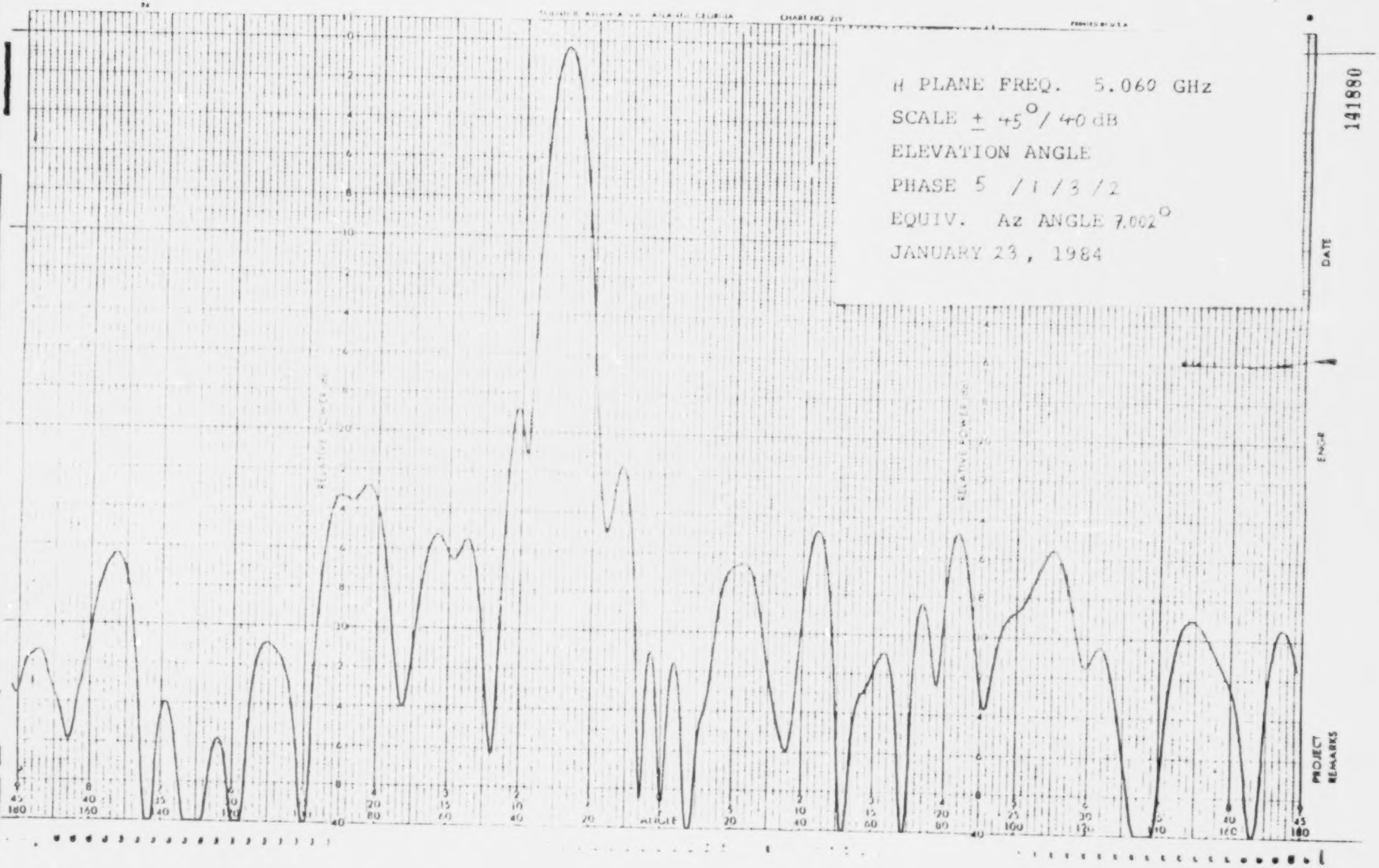


H PLANE FREQ. 5.060 GHz
SCALE ± 45°/ 40 dB
ELEVATION ANGLE
PHASE 5 / 0 / 11 / 3
EQUIV. Az ANGLE 8.987°
JANUARY 23 , 1984

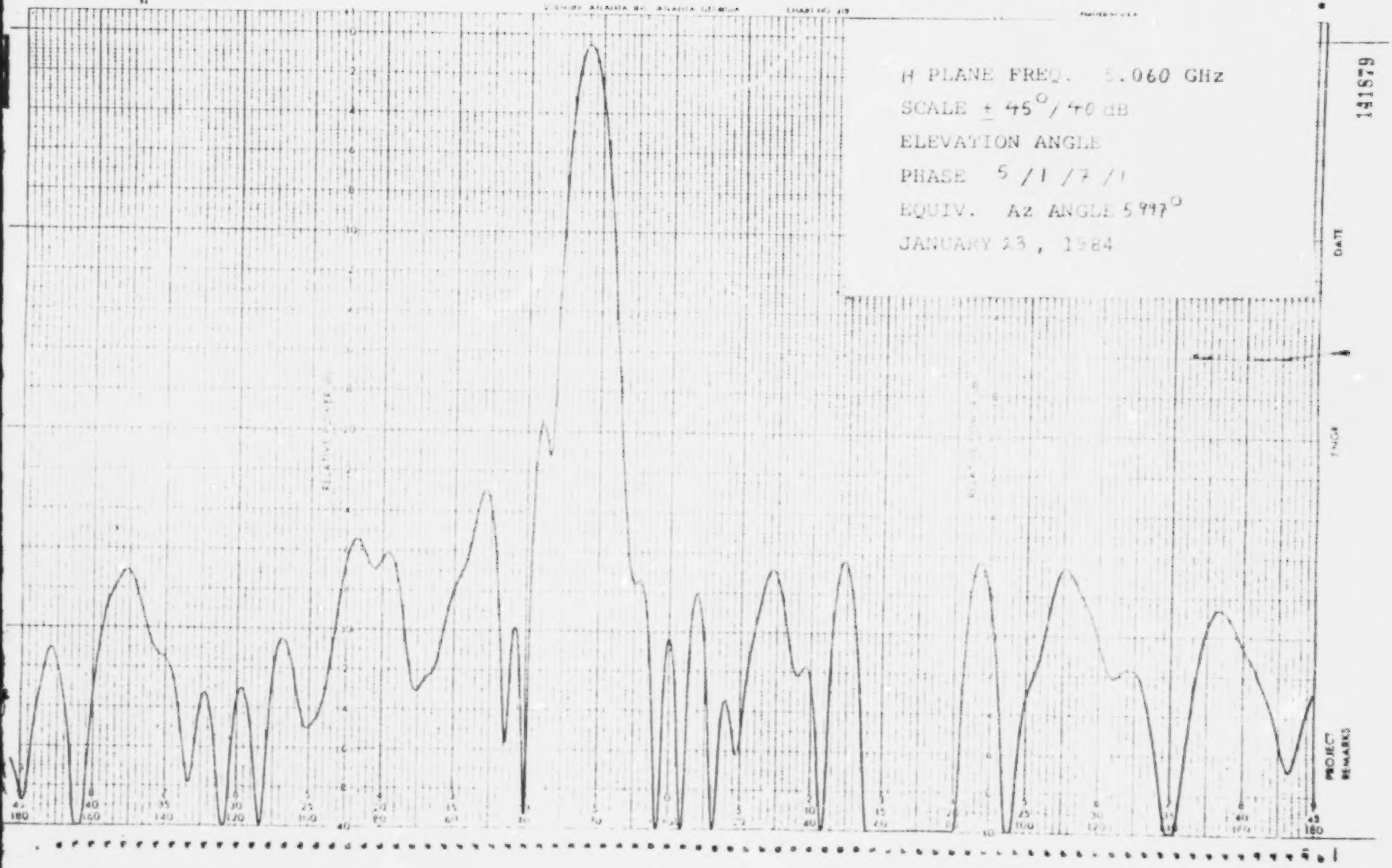
141882



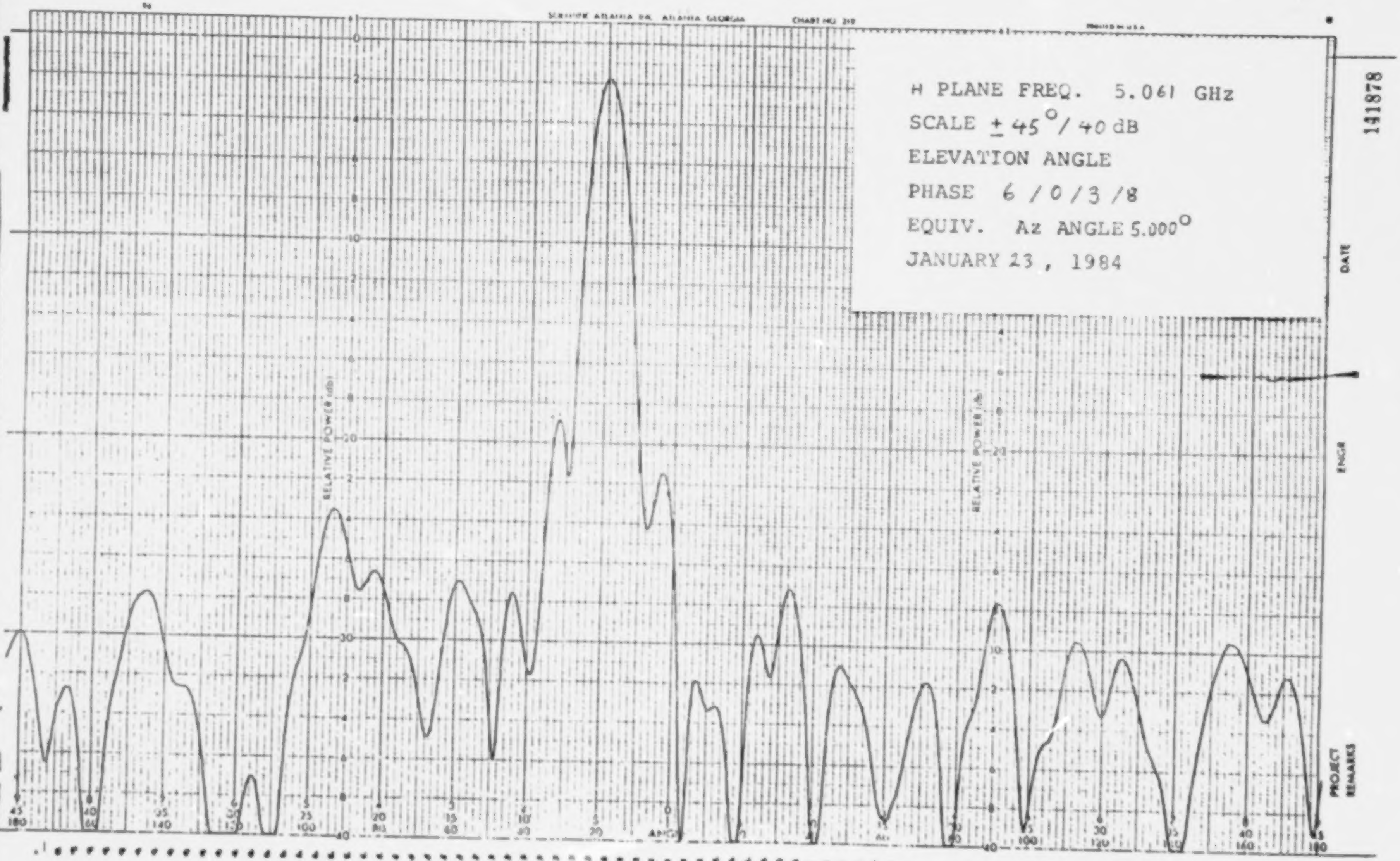
H PLANE FREQ. 5.060 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 5 /0 /15 /1
EQUIV. Az ANGLE 8.007°
JANUARY 23 , 1984



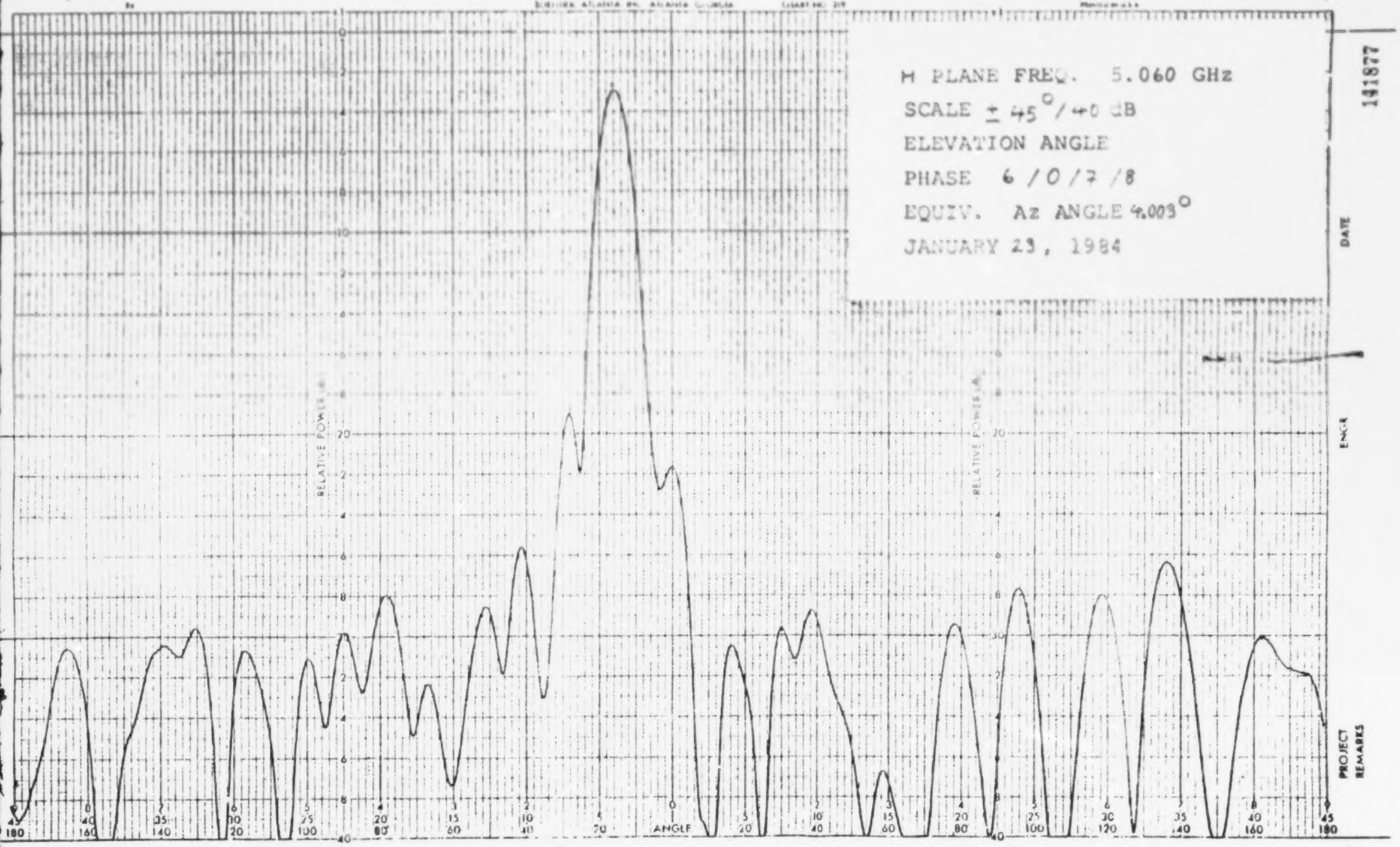
θ PLANE FREQ. 5.060 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 5 /1/3/2
EQUIV. Az ANGLE 7.002°
JANUARY 23, 1984



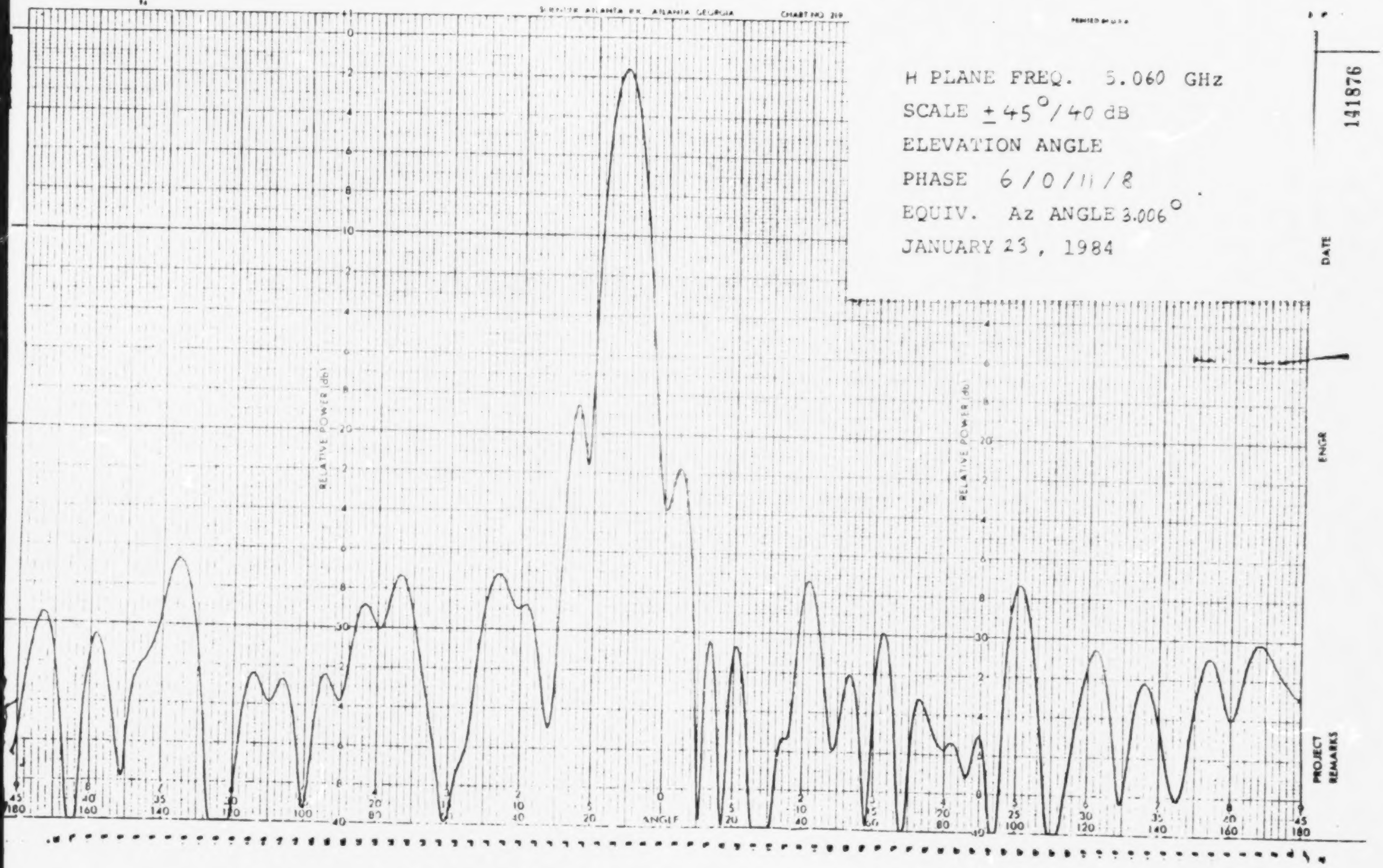
H PLANE FREQ. 5.060 GHz
SCALE ± 45°/ 40 dB
ELEVATION ANGLE
PHASE 5 /1 /7 /1
EQUIV. Az ANGLE 5.997°
JANUARY 23 , 1984



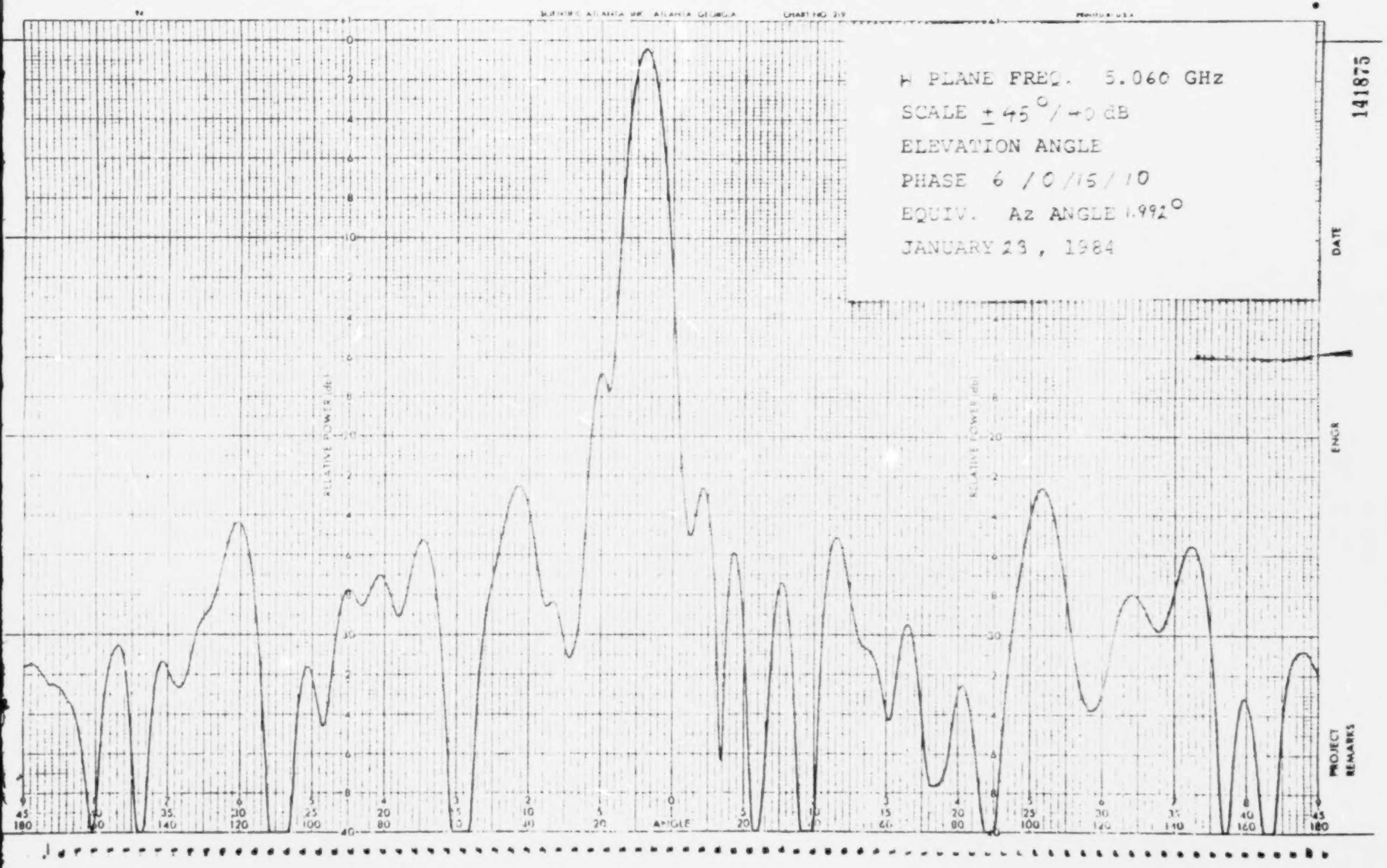
H PLANE FREQ. 5.061 GHz
SCALE ± 45°/ 40 dB
ELEVATION ANGLE
PHASE 6 / 0 / 3 / 8
EQUIV. Az ANGLE 5.000°
JANUARY 23 , 1984



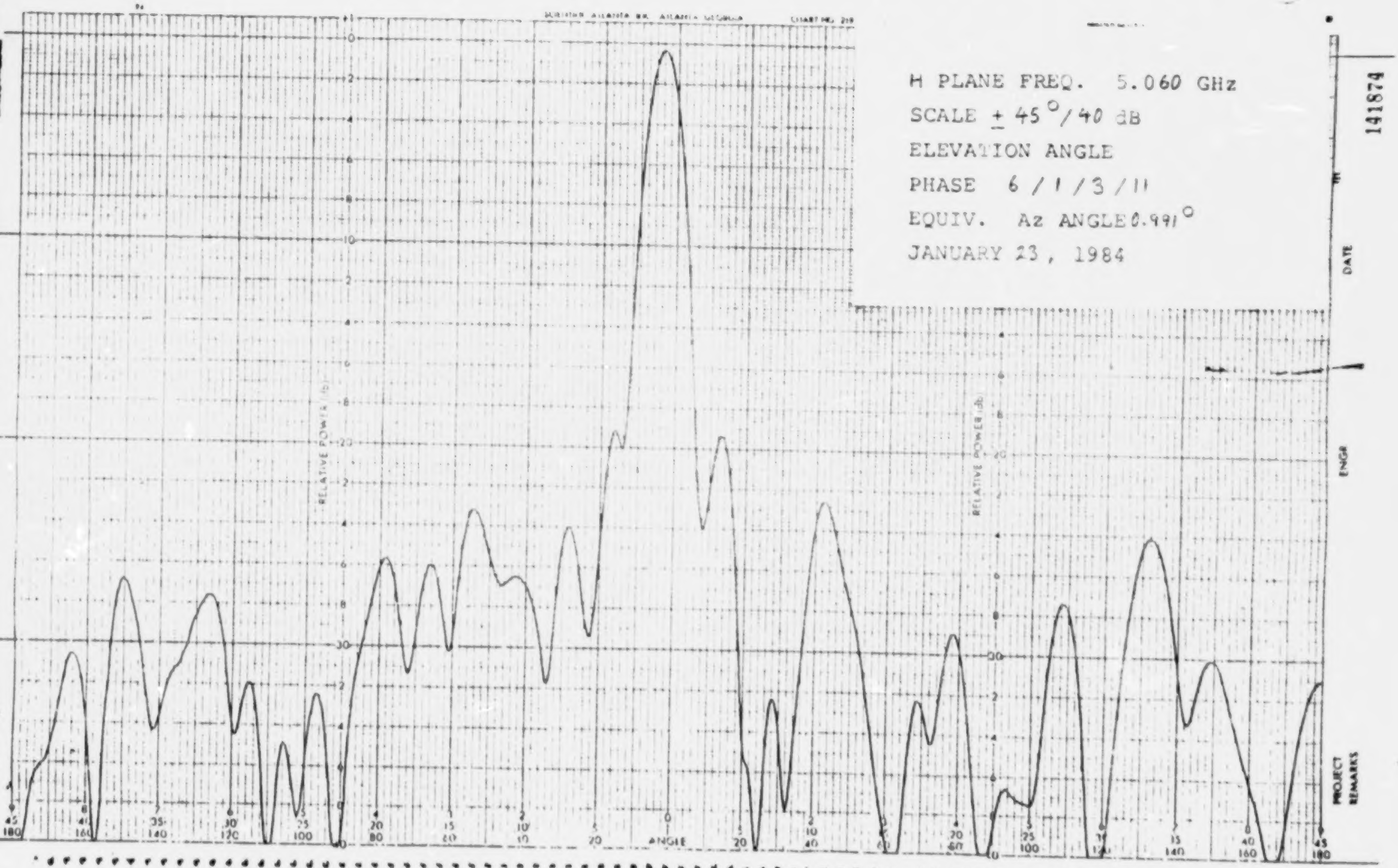
H PLANE FREQ. 5.060 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 6 /0 /7 /8
EQUIV. Az ANGLE 4.003°
JANUARY 23, 1984



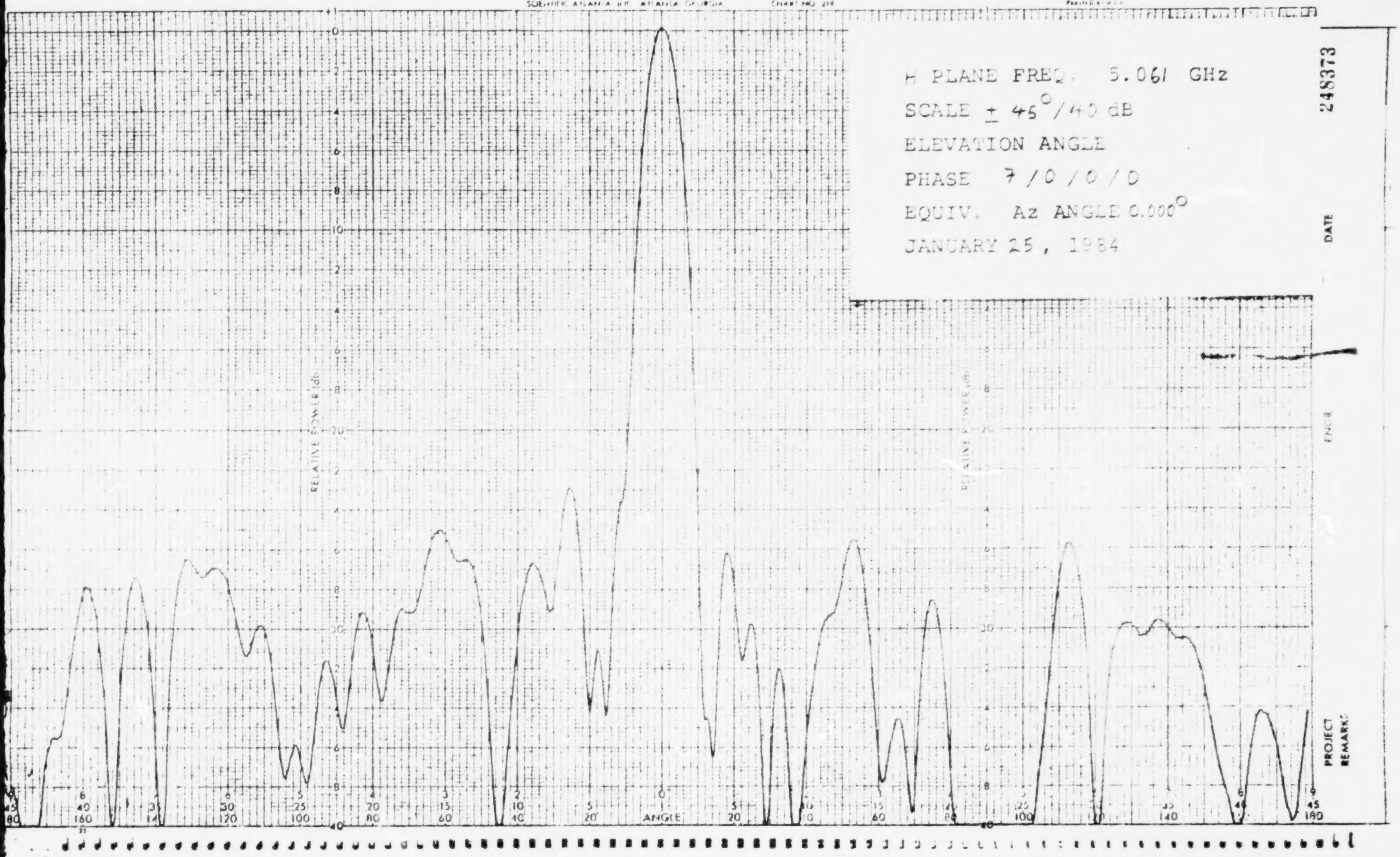
H PLANE FREQ. 5.060 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 6/0/11/8
EQUIV. Az ANGLE 3.006°
JANUARY 23, 1984

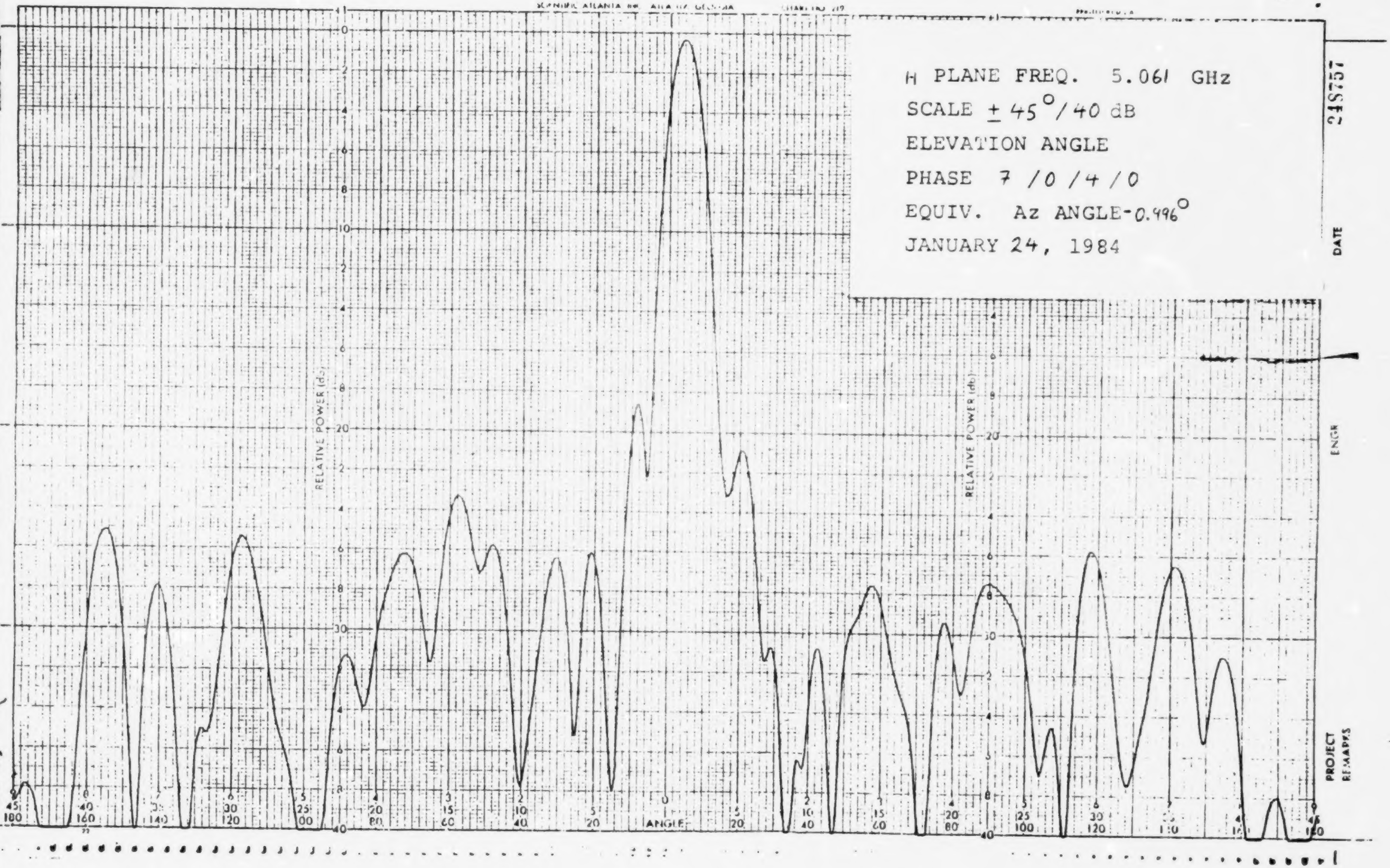


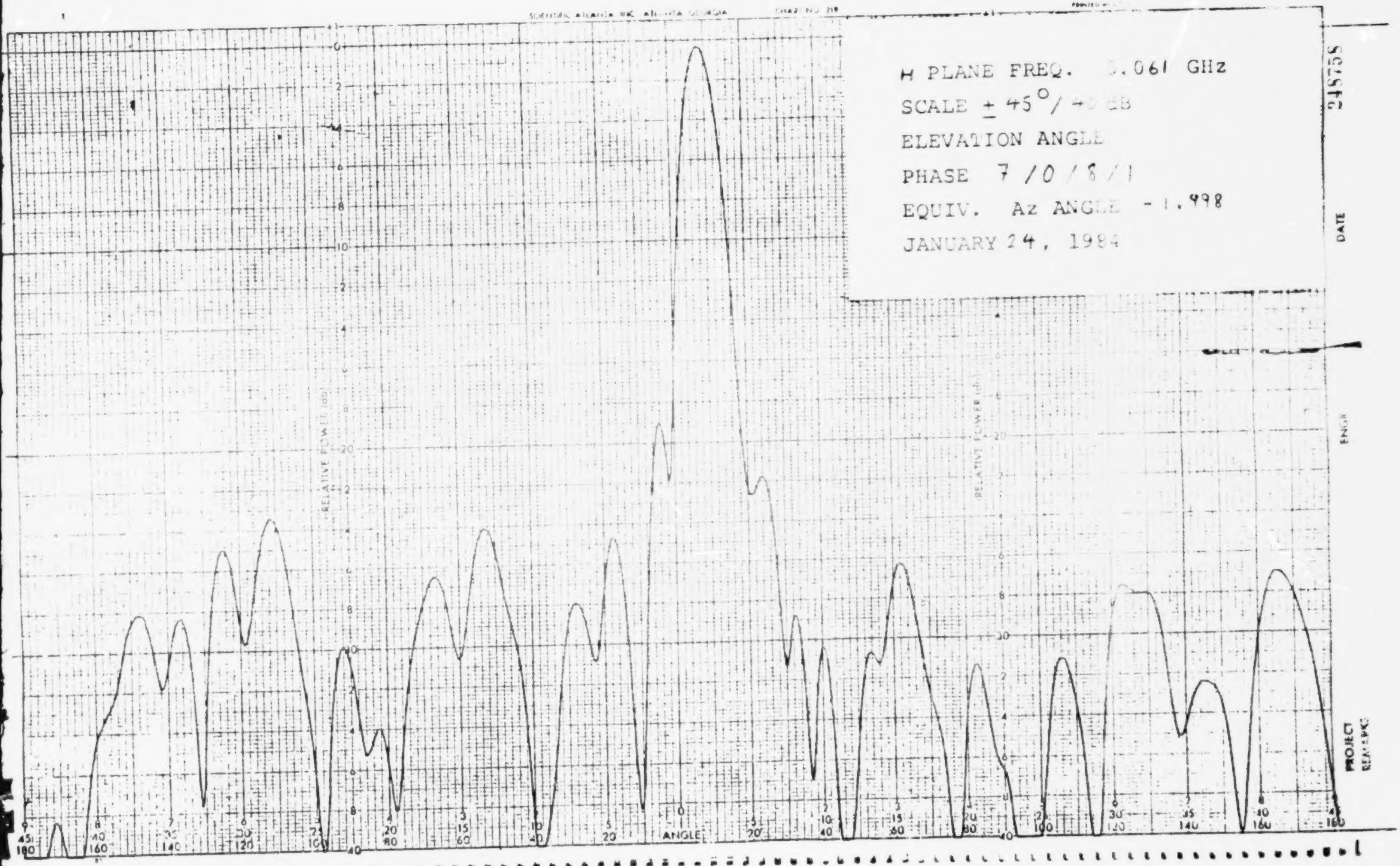
H PLANE FREQ. 5.060 GHz
SCALE ± 45°/ 40 dB
ELEVATION ANGLE
PHASE 6 / 0 / 15 / 10
EQUIV. Az ANGLE 1.992°
JANUARY 23 , 1984



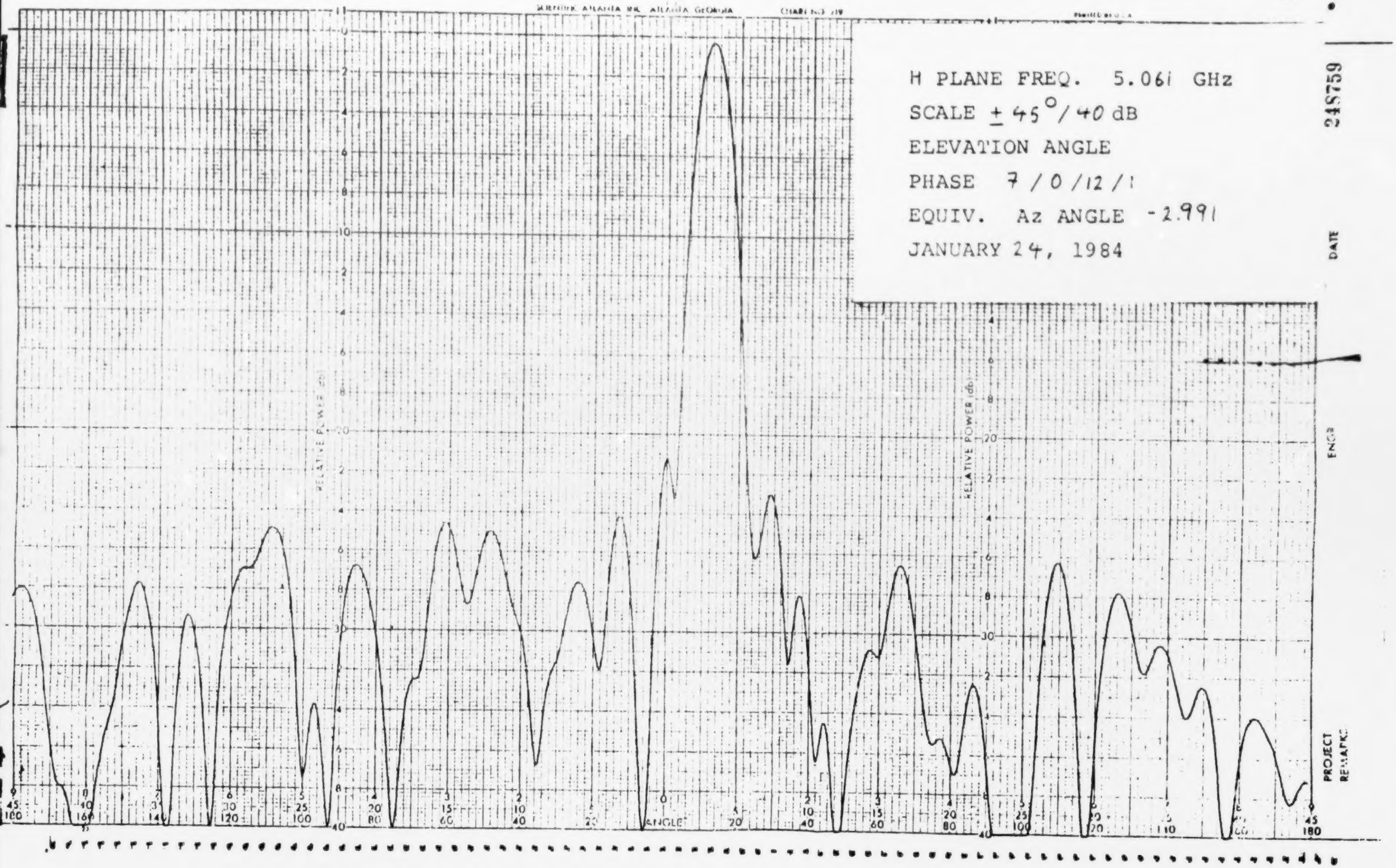
H PLANE FREQ. 5.060 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 6 / 1 / 3 / 11
EQUIV. Az ANGLE 0.991°
JANUARY 23, 1984


H PLANE FREQ. 5.061 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 7/0/0/0
EQUIV. Az ANGLE 0.000°
JANUARY 25, 1984

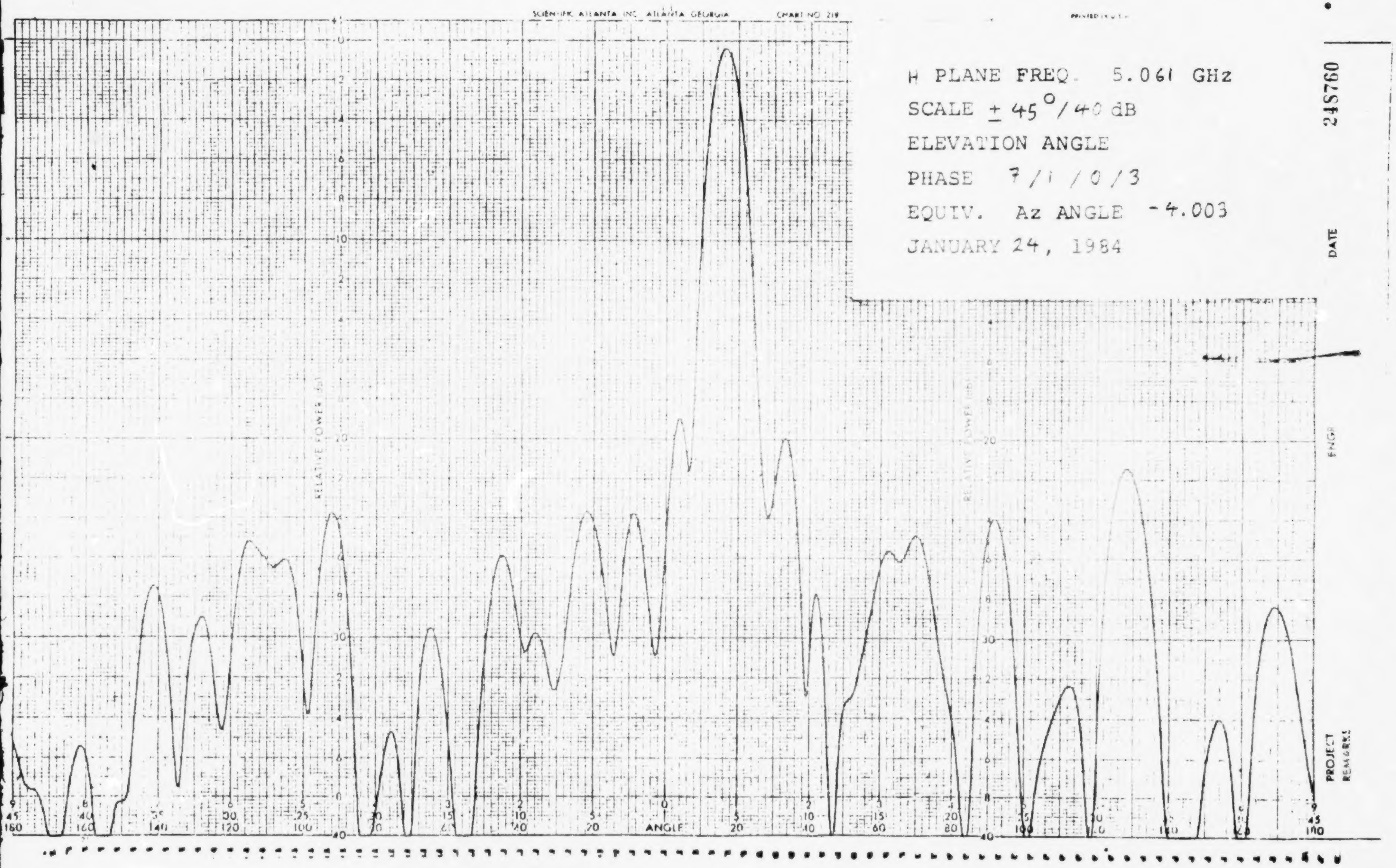

H PLANE FREQ. 5.061 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 7 /0 /4 /0
EQUIV. Az ANGLE-0.996°
JANUARY 24, 1984



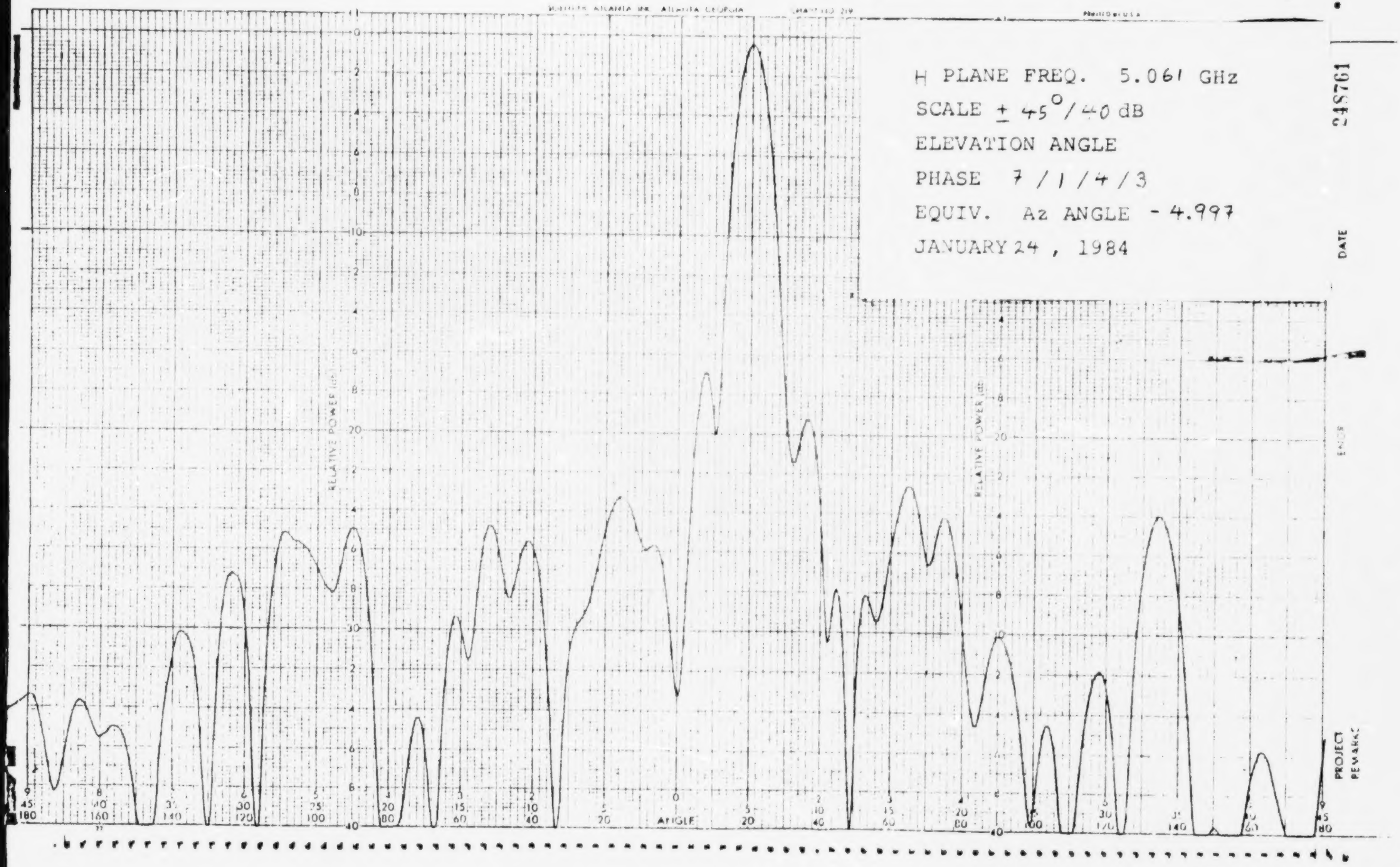
H PLANE FREQ. 5.061 GHz
SCALE ± 45°/ 40 dB
ELEVATION ANGLE
PHASE 7 / 0 / 8 / 1
EQUIV. Az ANGLE - 1.998
JANUARY 24, 1984



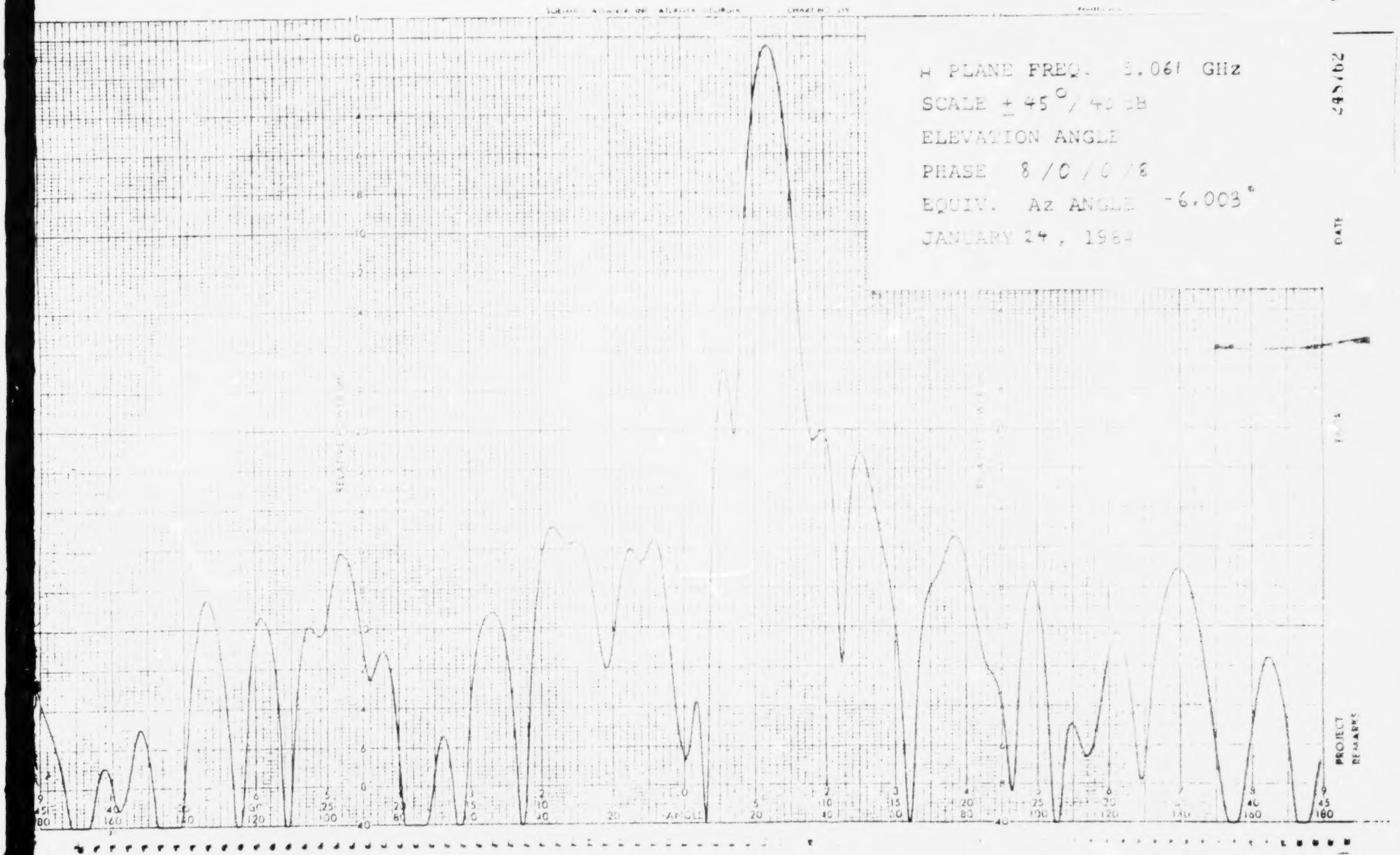
H PLANE FREQ. 5.061 GHz
SCALE ± 45°/ 40 dB
ELEVATION ANGLE
PHASE 7 / 0 /12 / 1
EQUIV. Az ANGLE -2.991
JANUARY 24, 1984



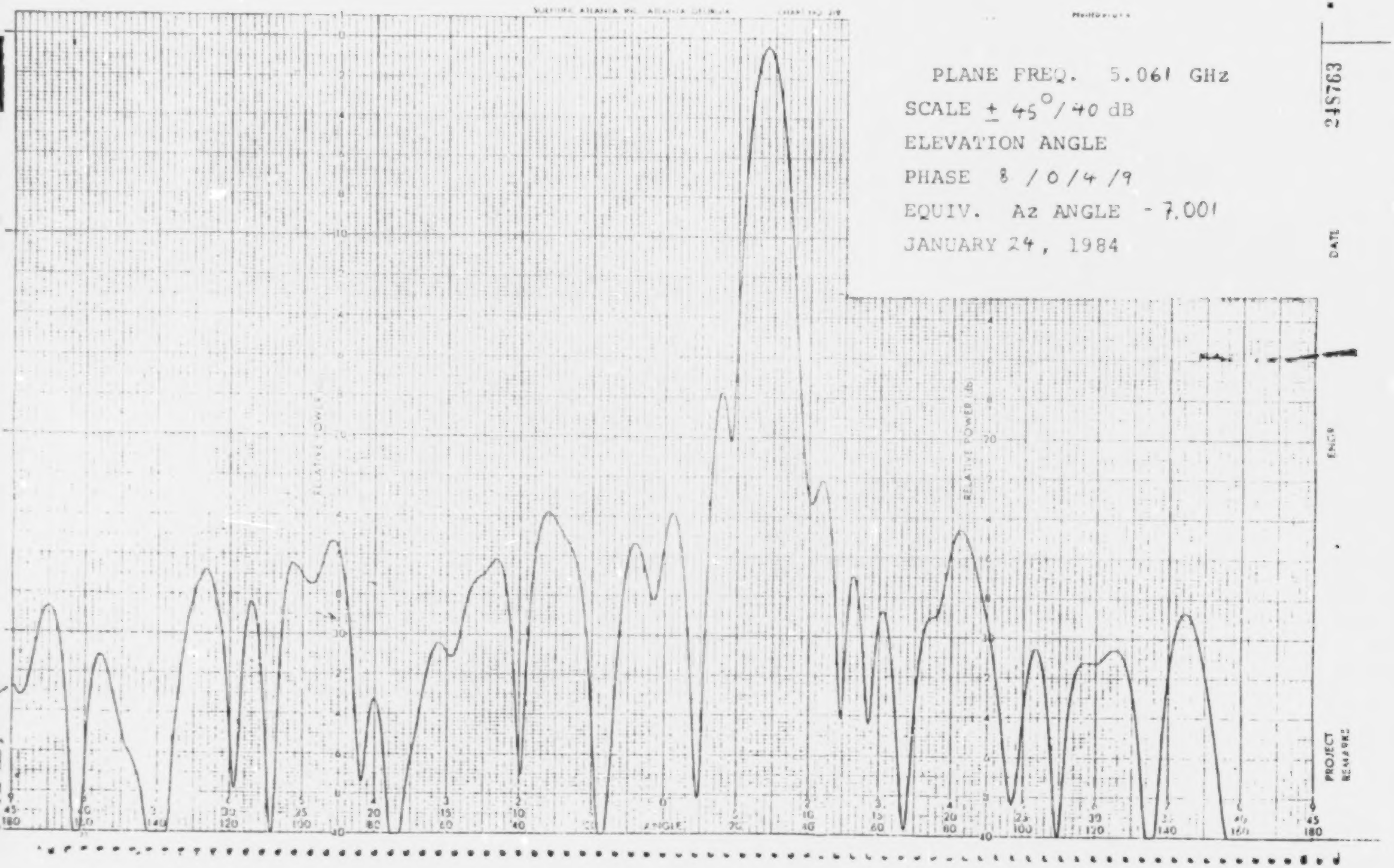
H PLANE FREQ. 5.061 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 7/1/0/3
EQUIV. Az ANGLE -4.003
JANUARY 24, 1984



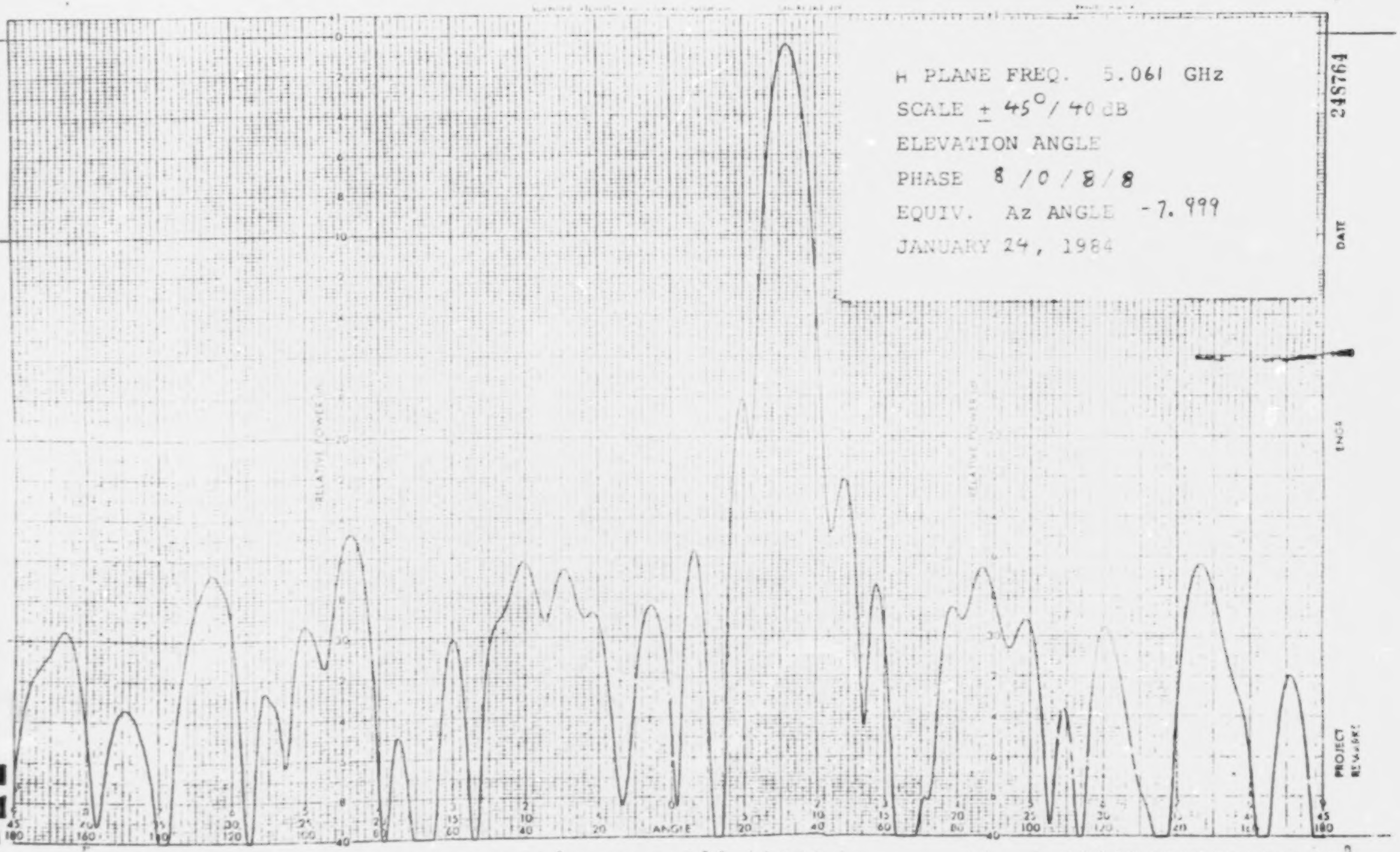
H PLANE FREQ. 5.061 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 7/1/4/3
EQUIV. Az ANGLE - 4.997
JANUARY 24, 1984



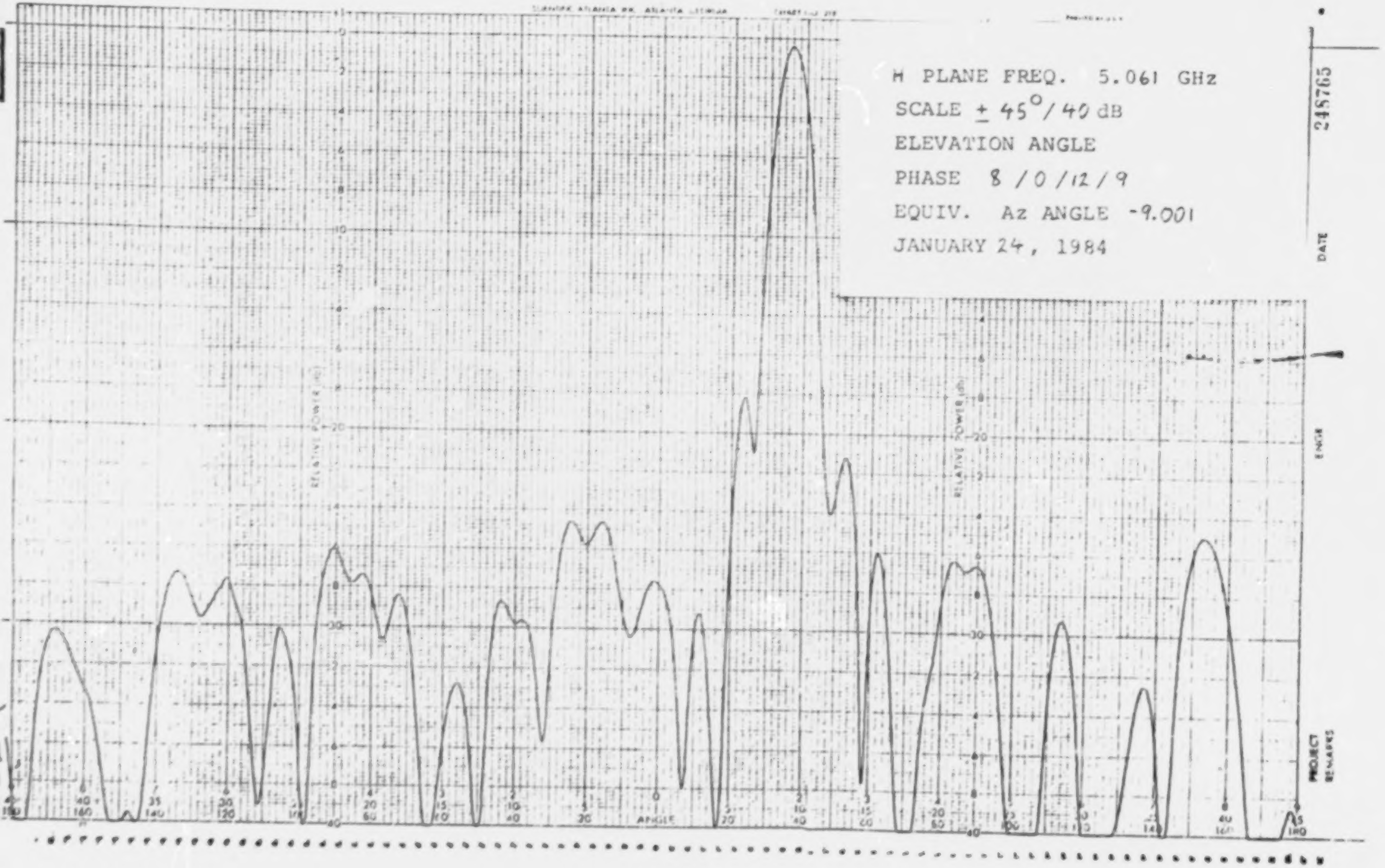
H PLANE FREQ. 3.061 GHz
SCALE ± 45°/ 40 dB
ELEVATION ANGLE
PHASE 8 / 0 / 0 /8
EQUIV. Az ANGLE -6.003°
JANUARY 24, 1984



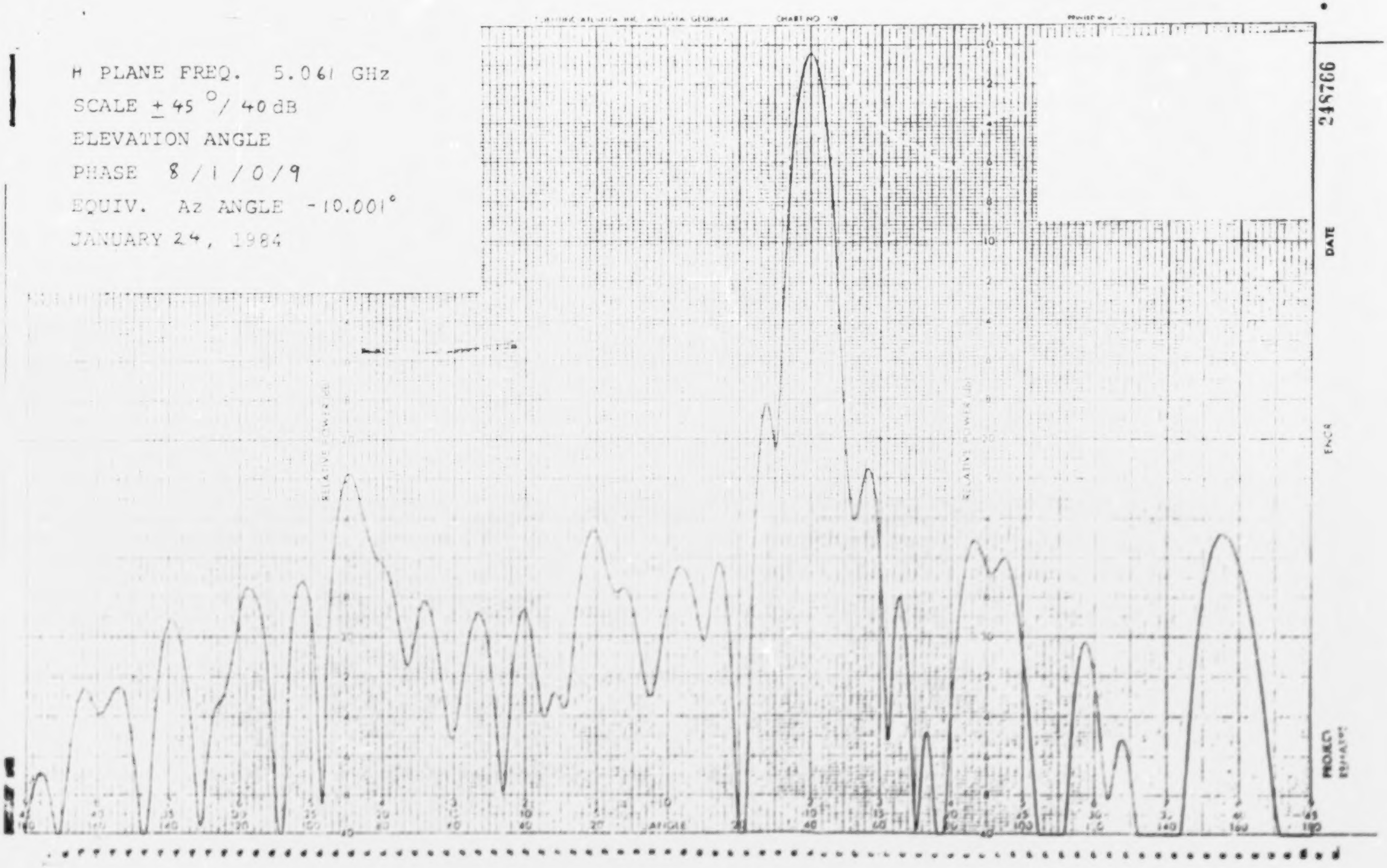
PLANE FREQ. 5.061 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 8 /0/4 /9
EQUIV. Az ANGLE - 7.001
JANUARY 24, 1984



H PLANE FREQ. 5.061 GHz
SCALE ± 45°/ 40 dB
ELEVATION ANGLE
PHASE 8 / 0 / 8 / 8
EQUIV. Az ANGLE -7.999
JANUARY 24, 1984

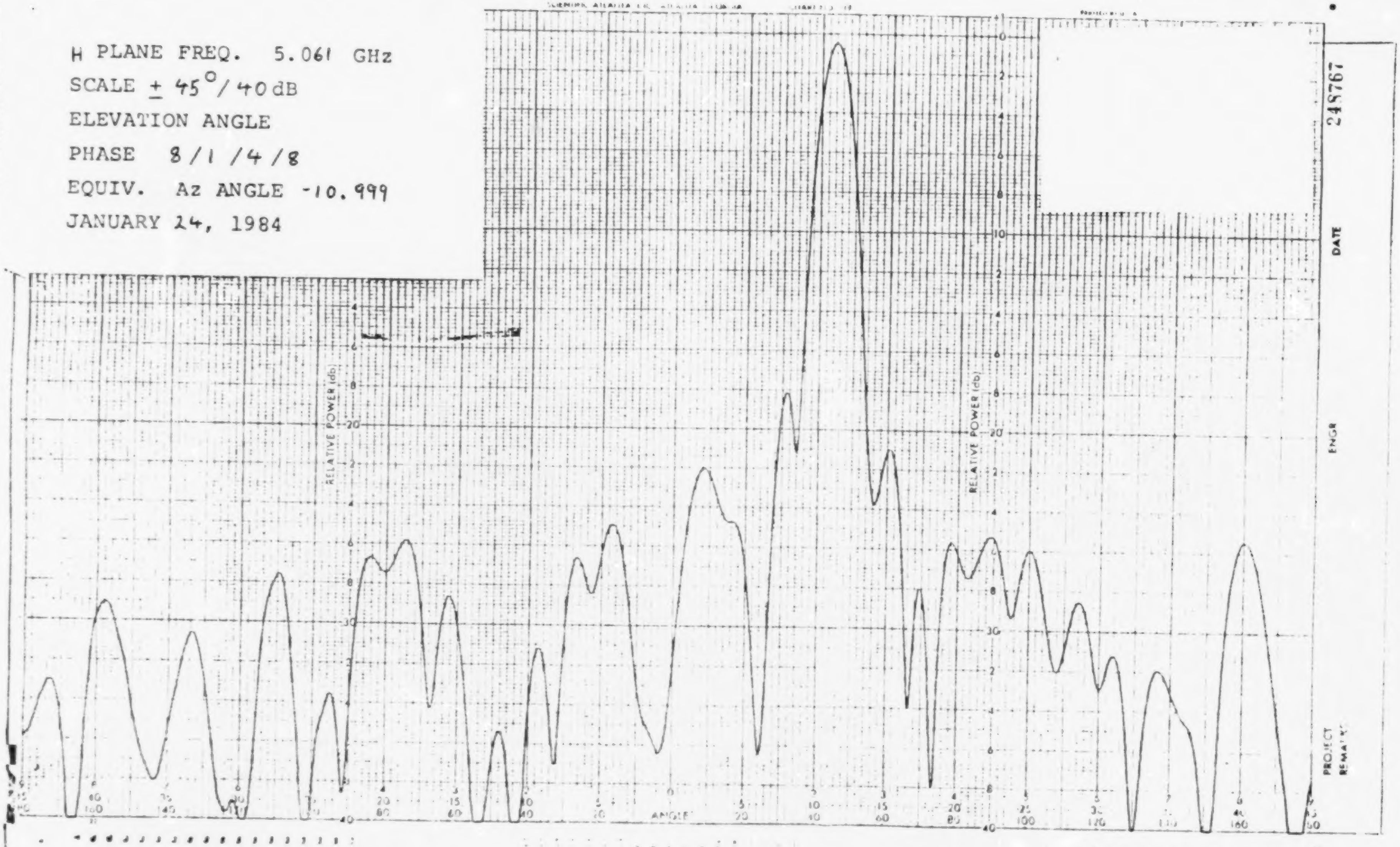


H PLANE FREQ. 5.061 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 8 /0 /12 /9
EQUIV. Az ANGLE -9.001
JANUARY 24, 1984

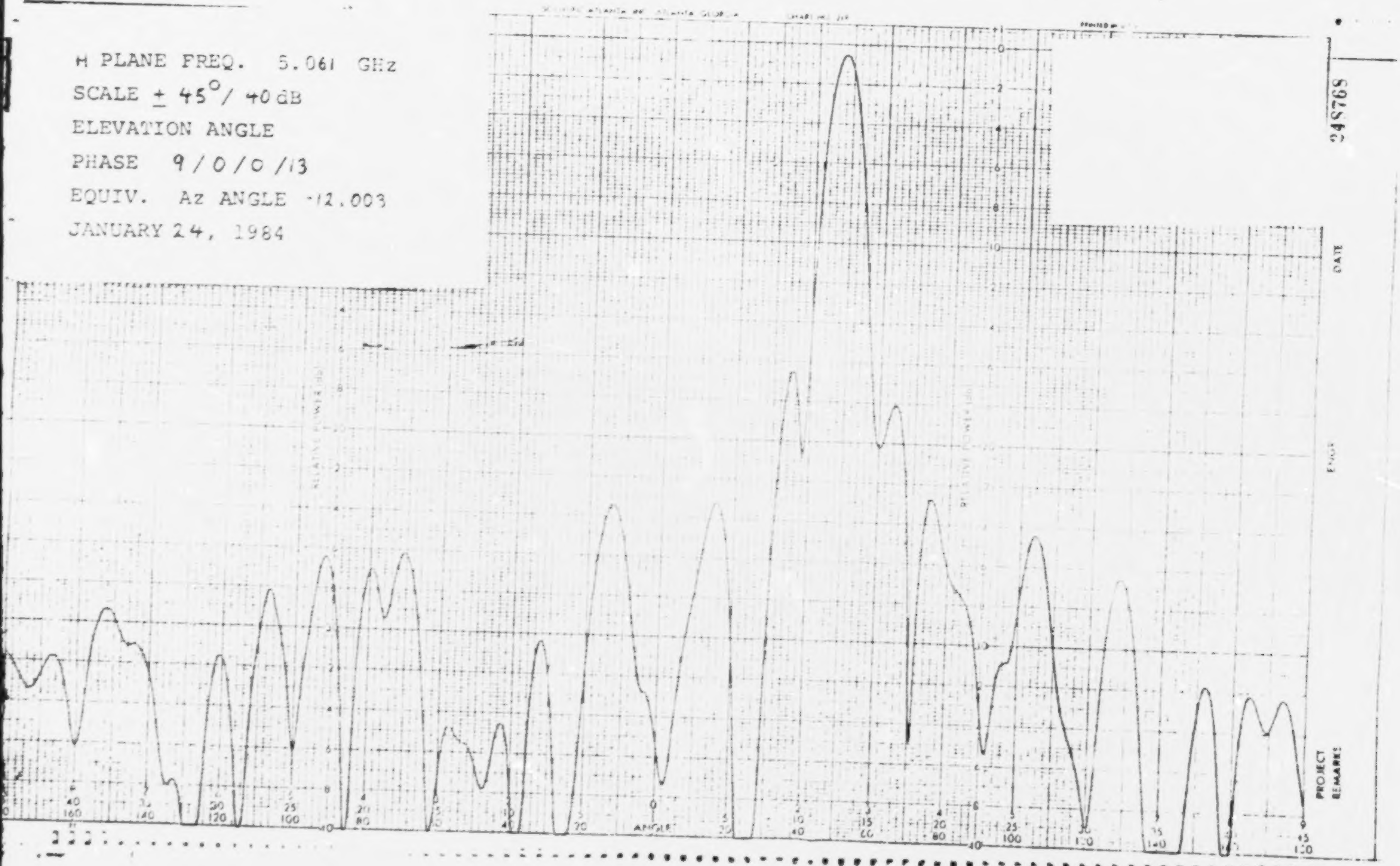


H PLANE FREQ. 5.061 GHz
SCALE ± 45 °/ 40 dB
ELEVATION ANGLE
PHASE 8 / 1 / 0 / 9
EQUIV. Az ANGLE -10.001°
JANUARY 24, 1984

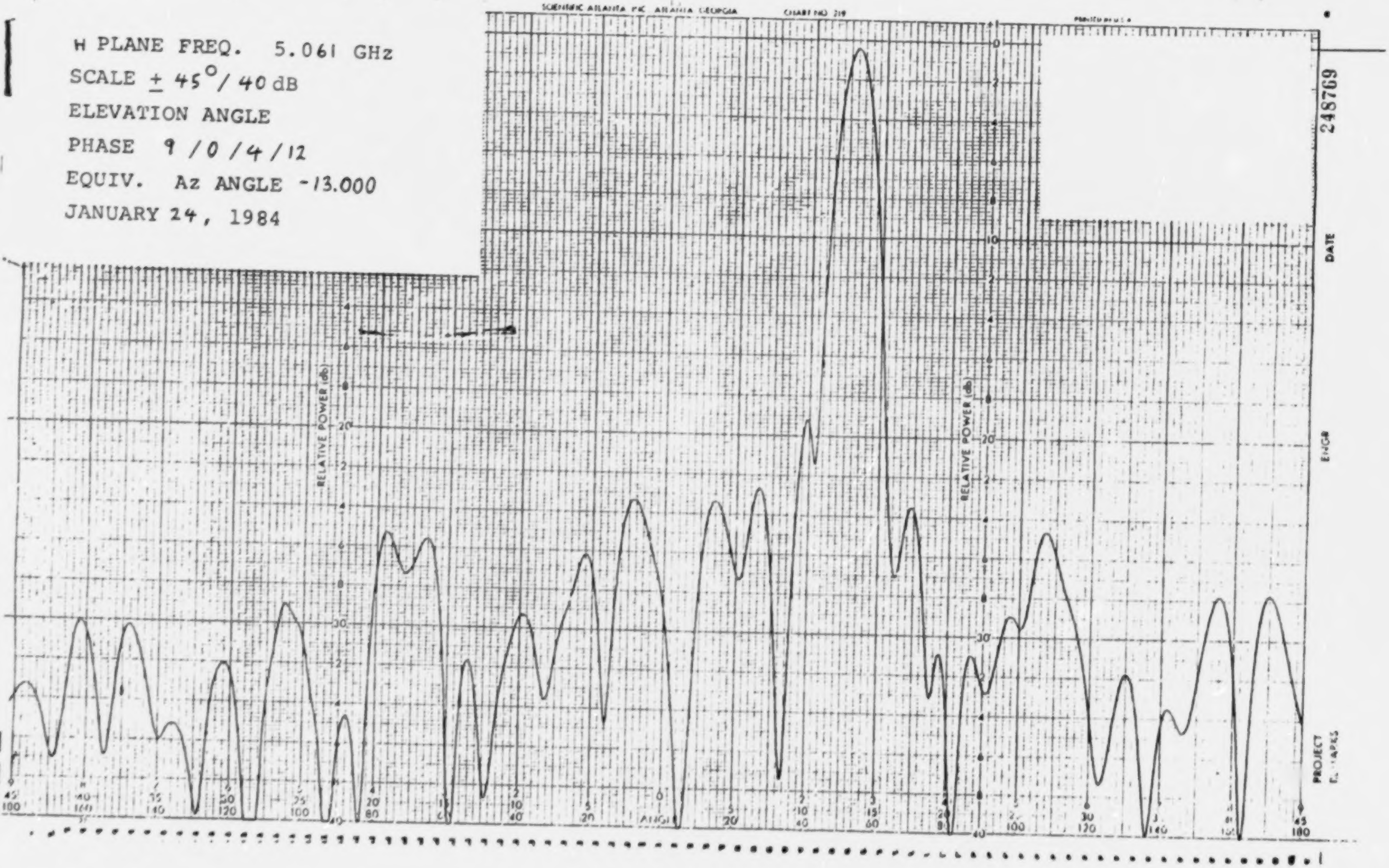
H PLANE FREQ. 5.061 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 8/1/4/8
EQUIV. Az ANGLE -10.999
JANUARY 24, 1984



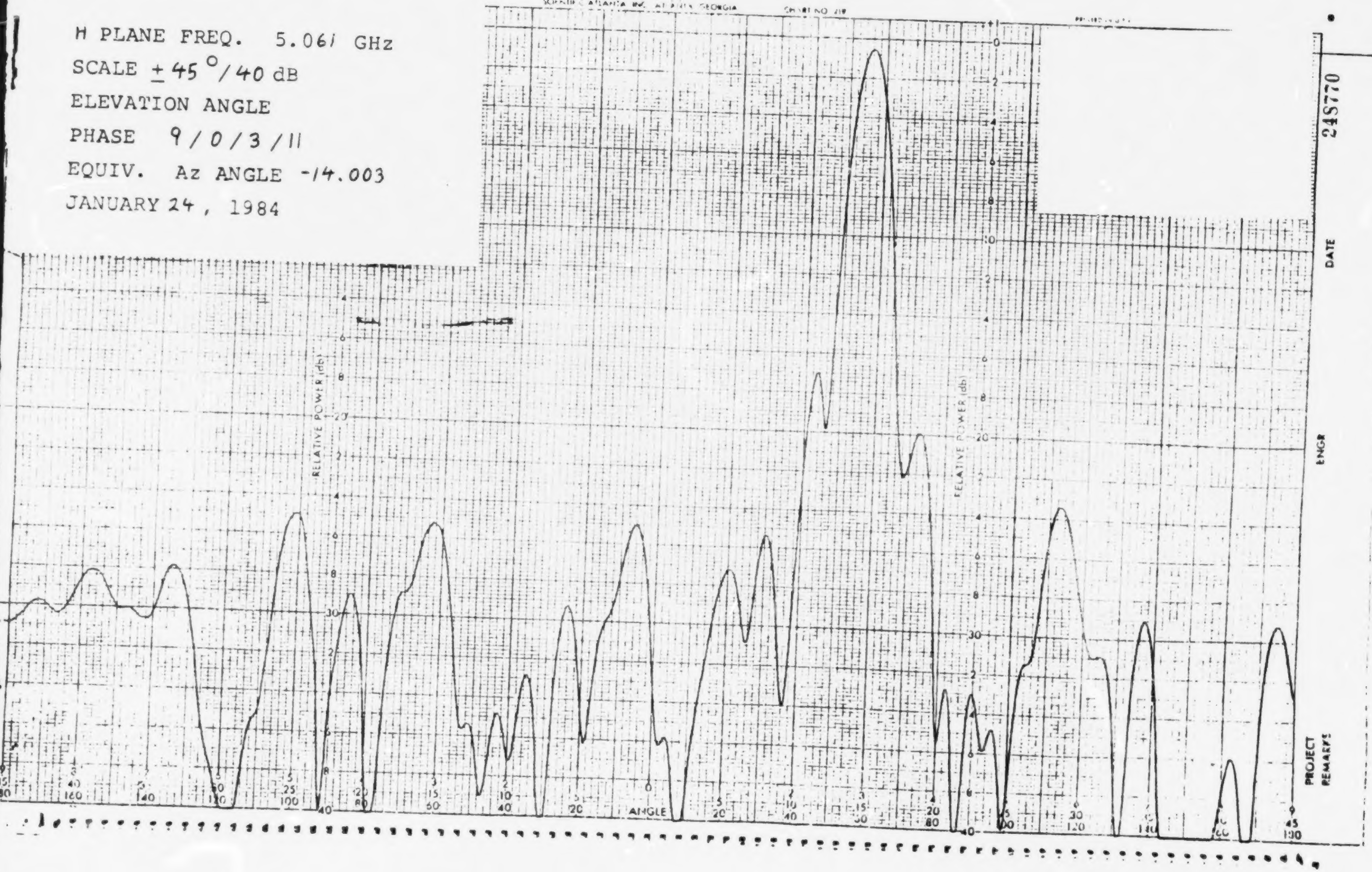
H PLANE FREQ. 5.061 GHz
SCALE ± 45°/ 40 dB
ELEVATION ANGLE
PHASE 9/0/0/13
EQUIV. Az ANGLE -12.003
JANUARY 24, 1984



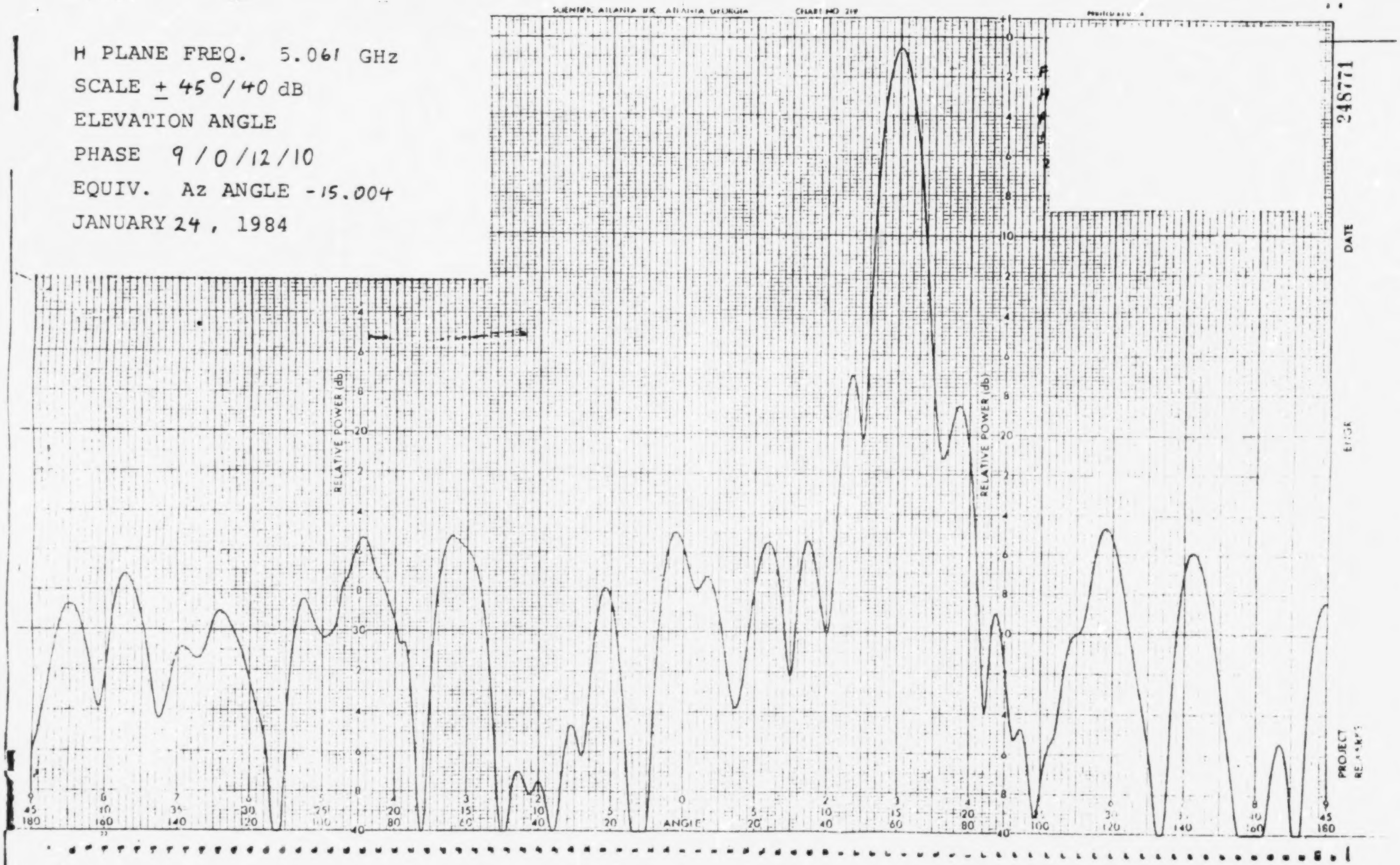
H PLANE FREQ. 5.061 GHz
SCALE ± 45°/ 40 dB
ELEVATION ANGLE
PHASE 9 / 0 / 4 / 12
EQUIV. Az ANGLE -13.000
JANUARY 24, 1984



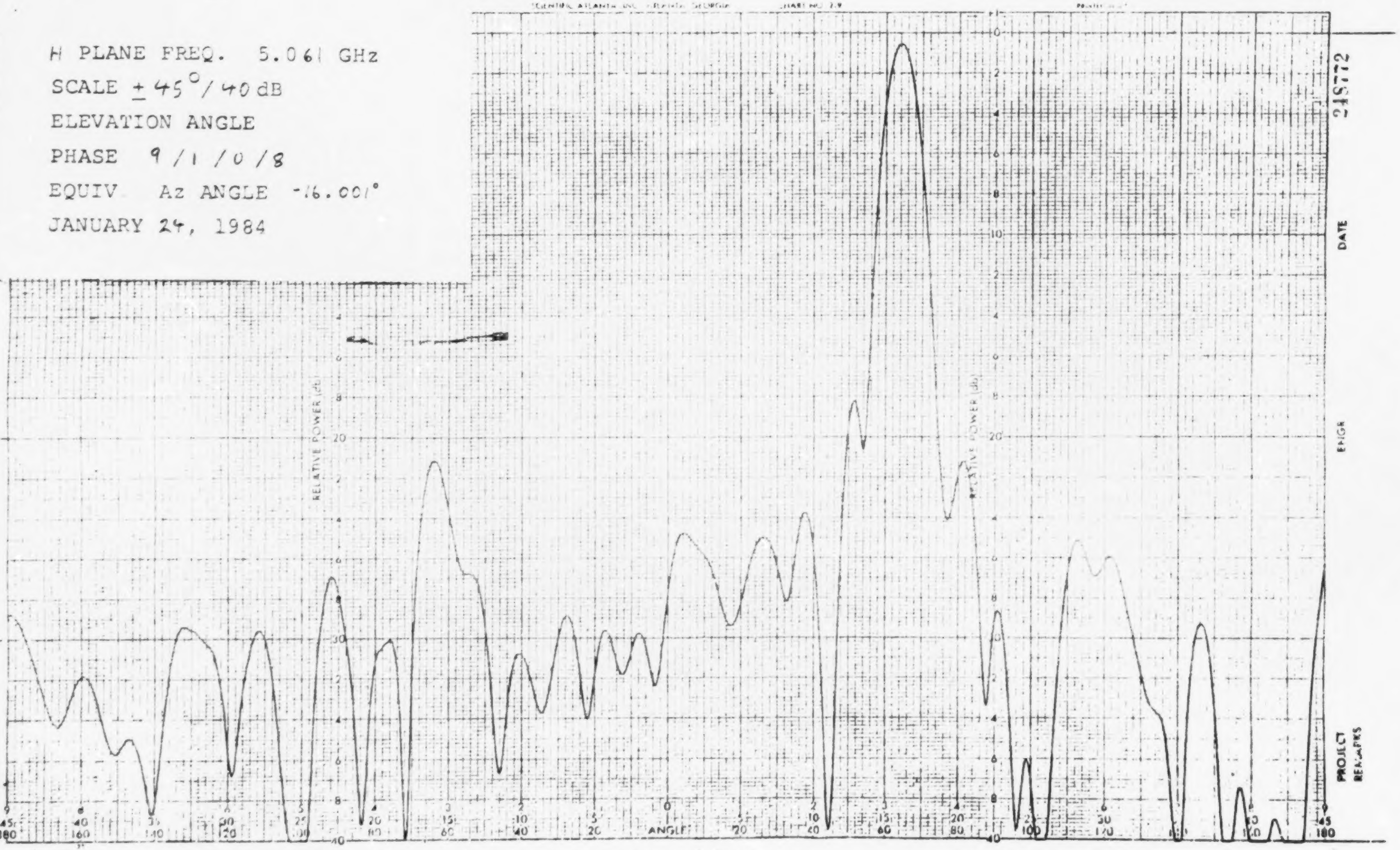
H PLANE FREQ. 5.061 GHz
SCALE ± 45 °/40 dB
ELEVATION ANGLE
PHASE 9/0/3/11
EQUIV. Az ANGLE -14.003
JANUARY 24, 1984



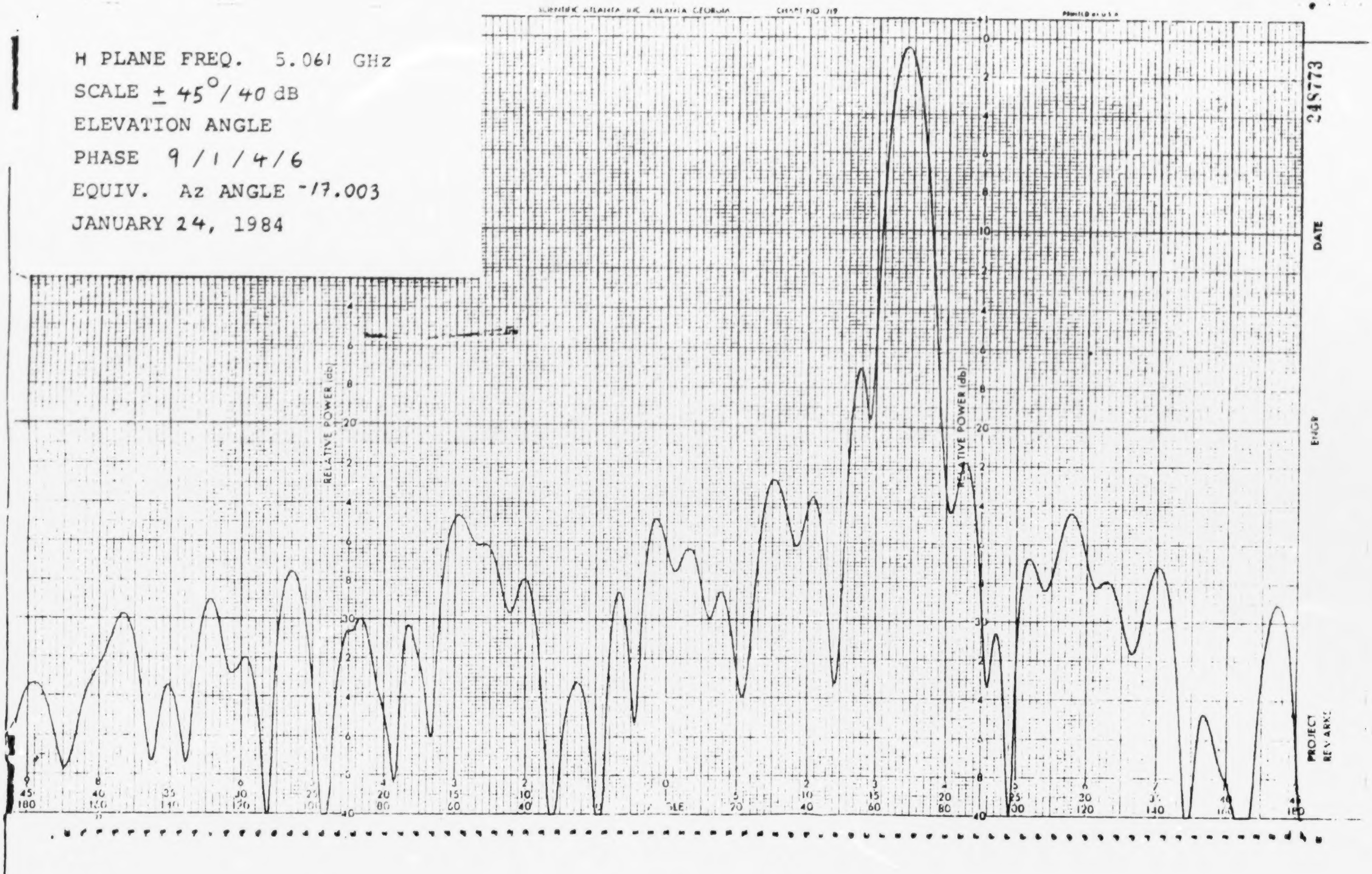
H PLANE FREQ. 5.061 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 9/0/12/10
EQUIV. Az ANGLE -15.004
JANUARY 24, 1984



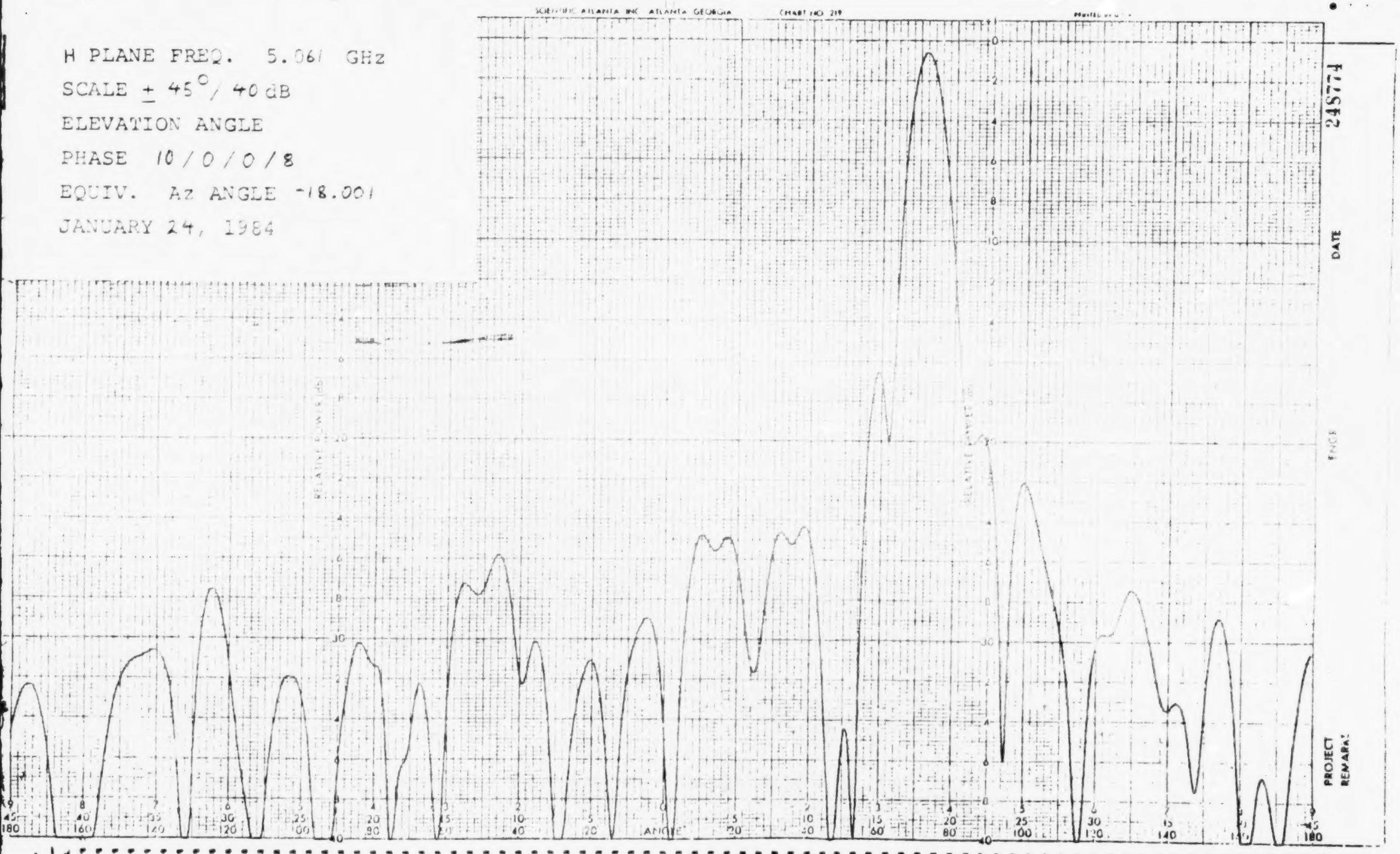
H PLANE FREQ. 5.061 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 9/1/0/8
EQUIV Az ANGLE -16.001°
JANUARY 24, 1984



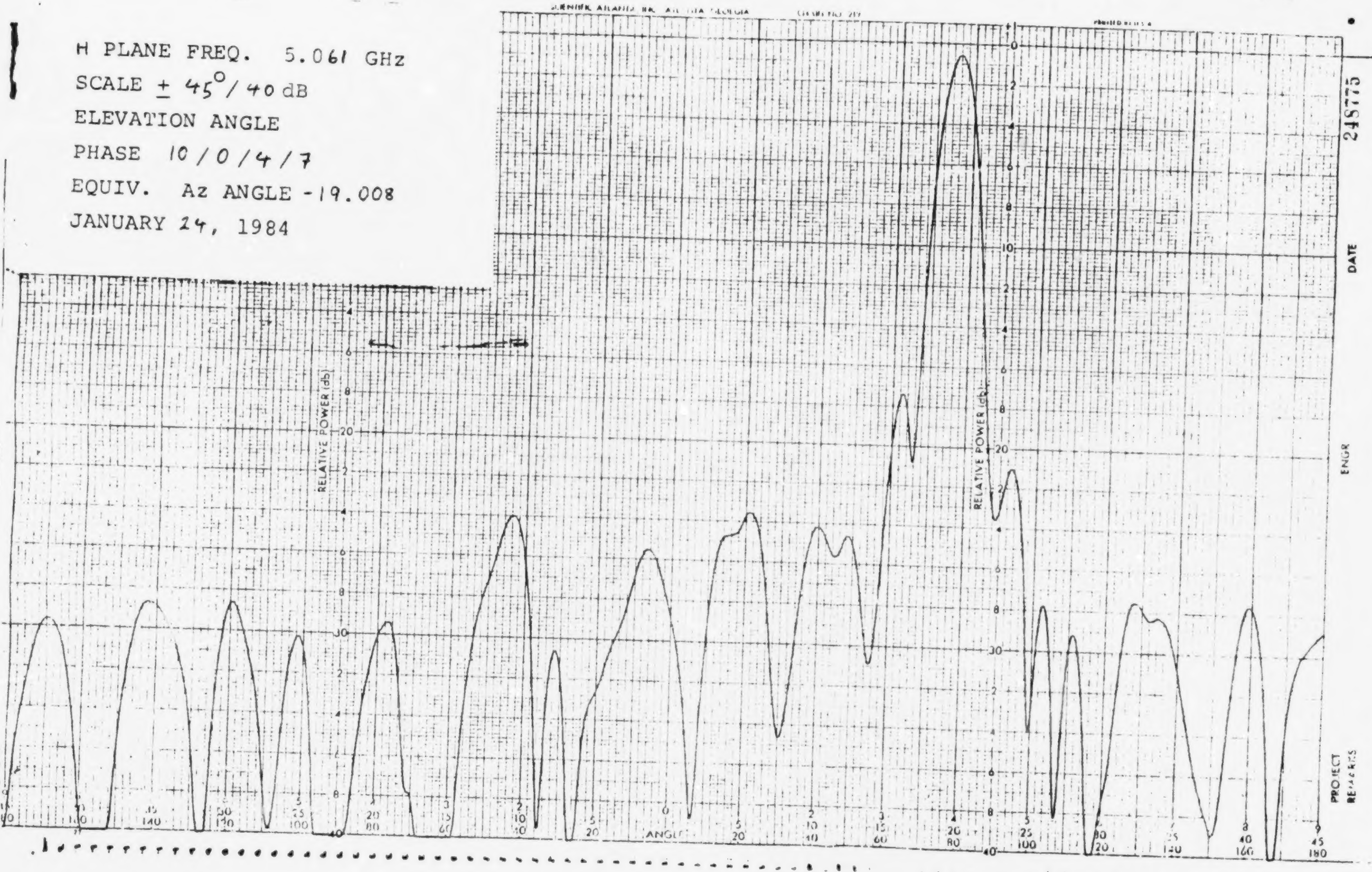
H PLANE FREQ. 5.061 GHz
SCALE ± 45°/ 40 dB
ELEVATION ANGLE
PHASE 9 / 1 / 4 / 6
EQUIV. Az ANGLE -17.003
JANUARY 24, 1984



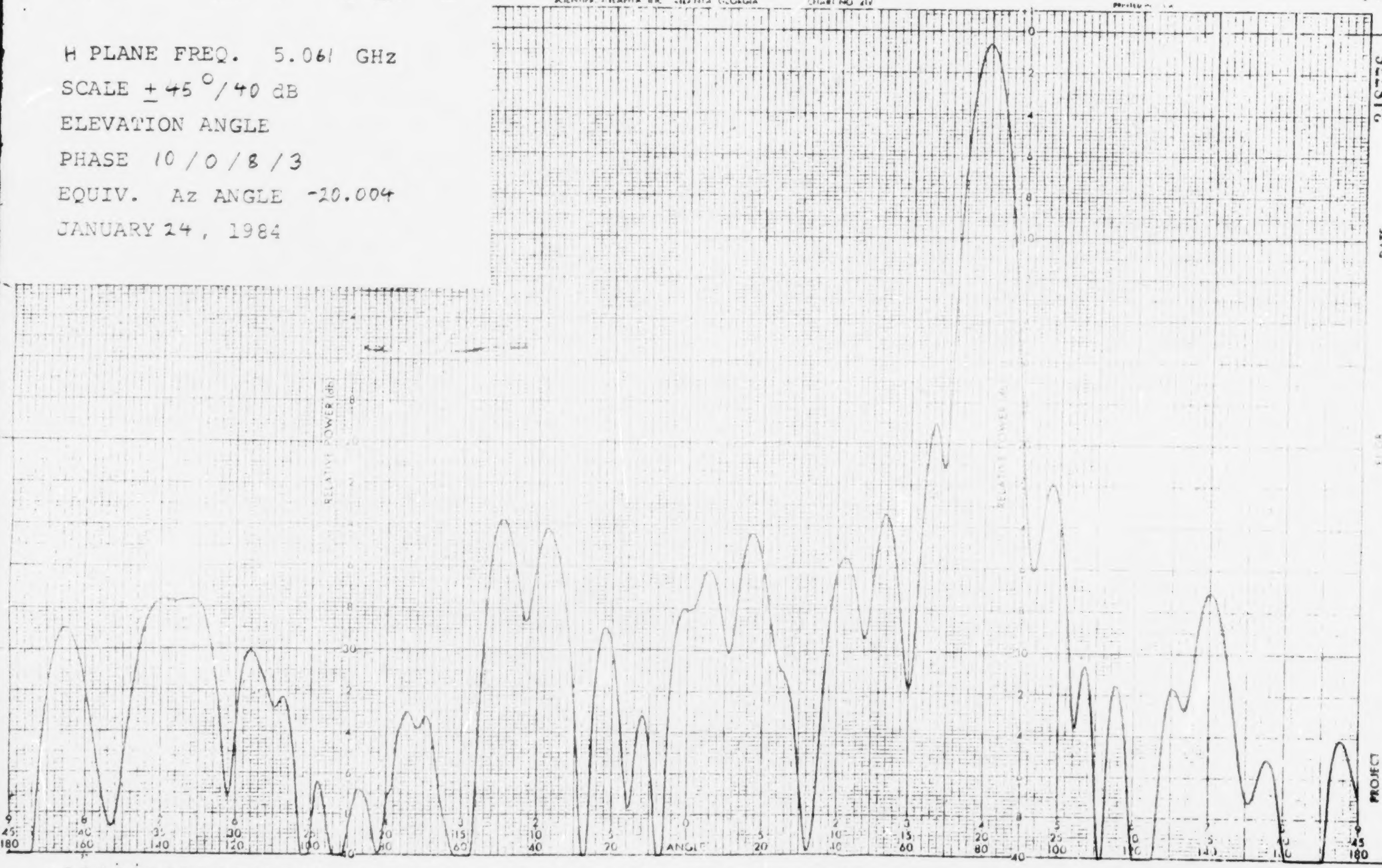
H PLANE FREQ. 5.061 GHz
SCALE ± 45°/ 40 dB
ELEVATION ANGLE
PHASE 10/0/0/8
EQUIV. Az ANGLE -18.001
JANUARY 24, 1984



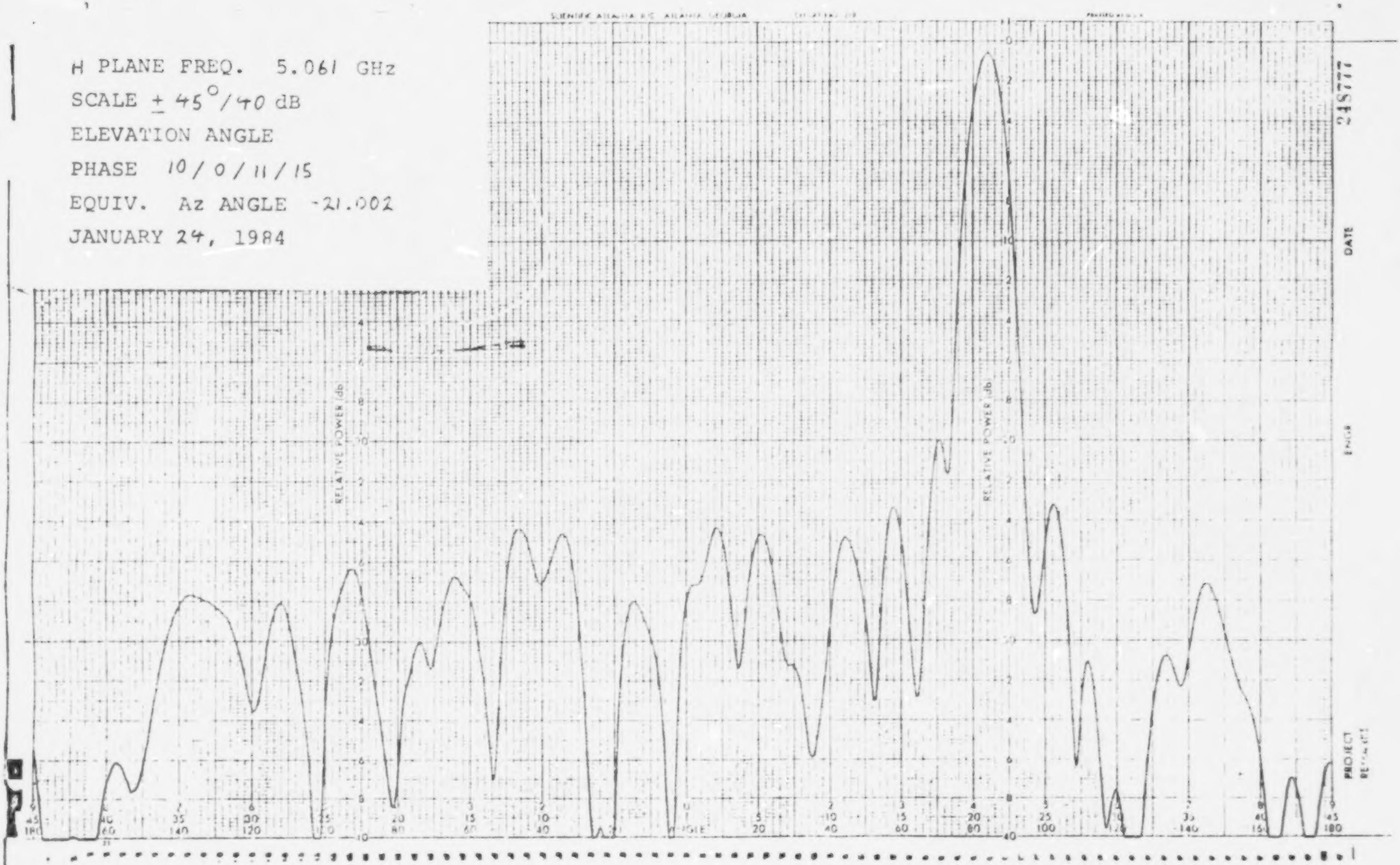
H PLANE FREQ. 5.061 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 10/0/4/7
EQUIV. Az ANGLE -19.008
JANUARY 24, 1984

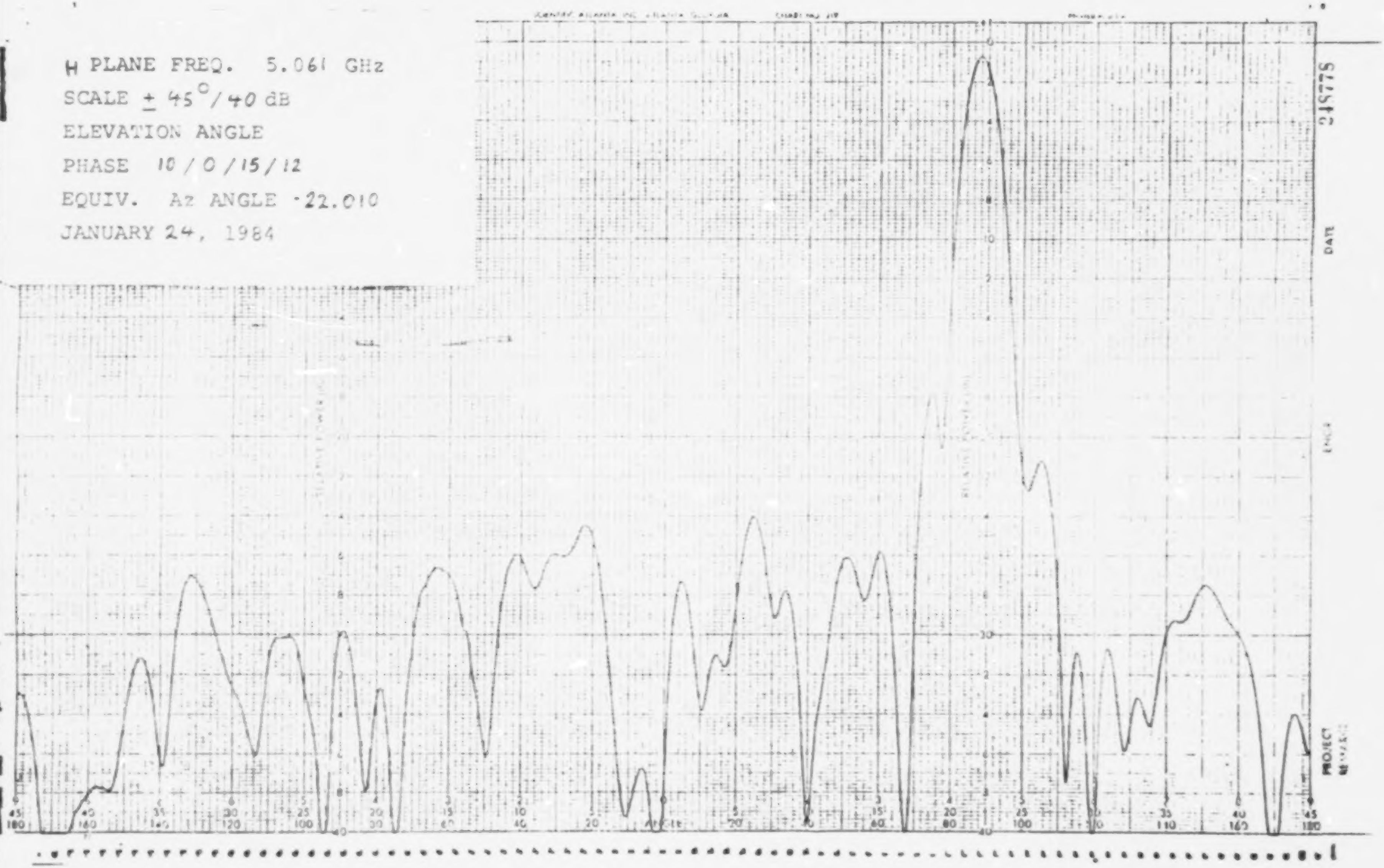


H PLANE FREQ. 5.061 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 10/0/8/3
EQUIV. Az ANGLE -20.004
JANUARY 24, 1984



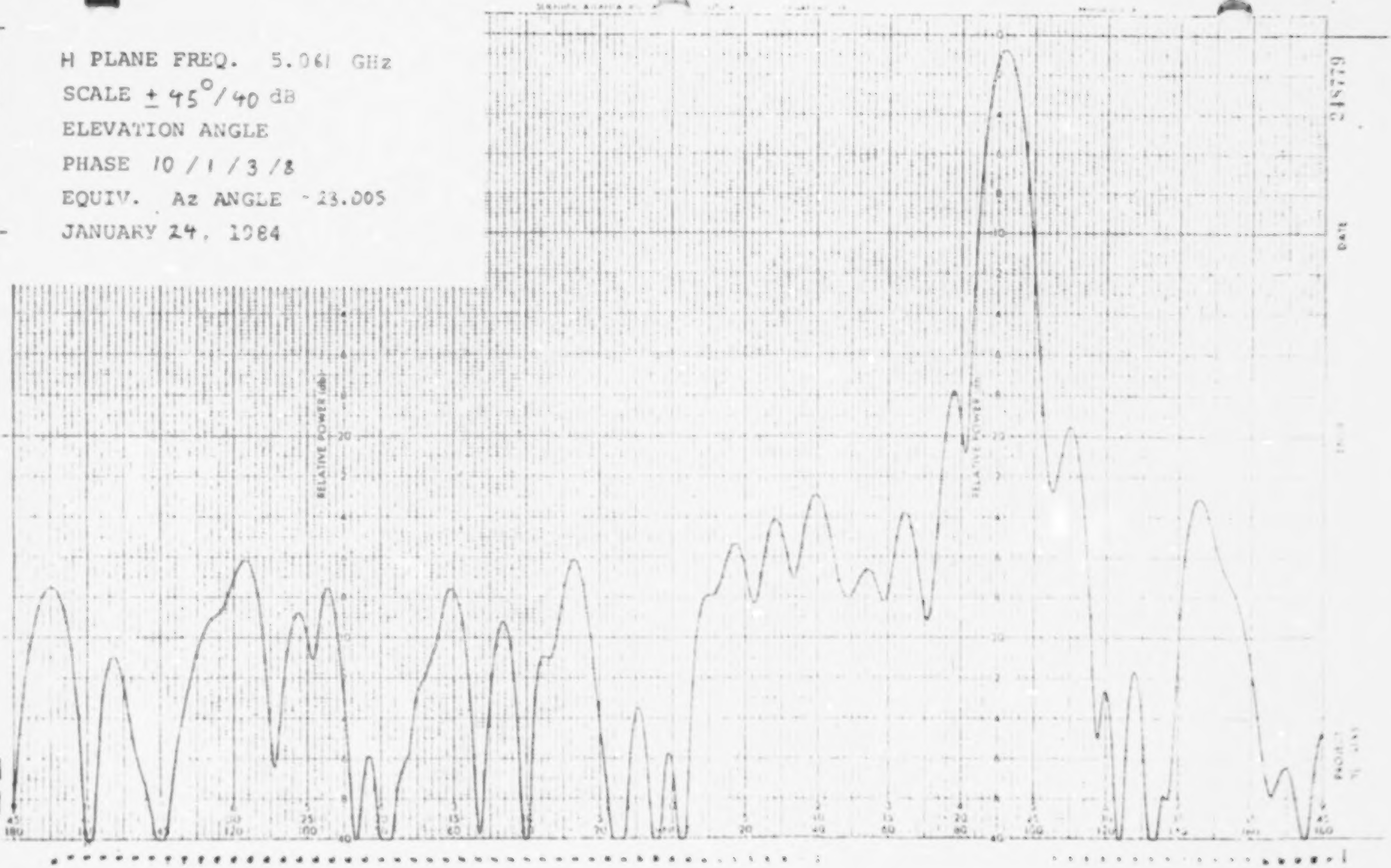
H PLANE FREQ. 5.061 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 10/0/11/15
EQUIV. Az ANGLE -21.002
JANUARY 24, 1984



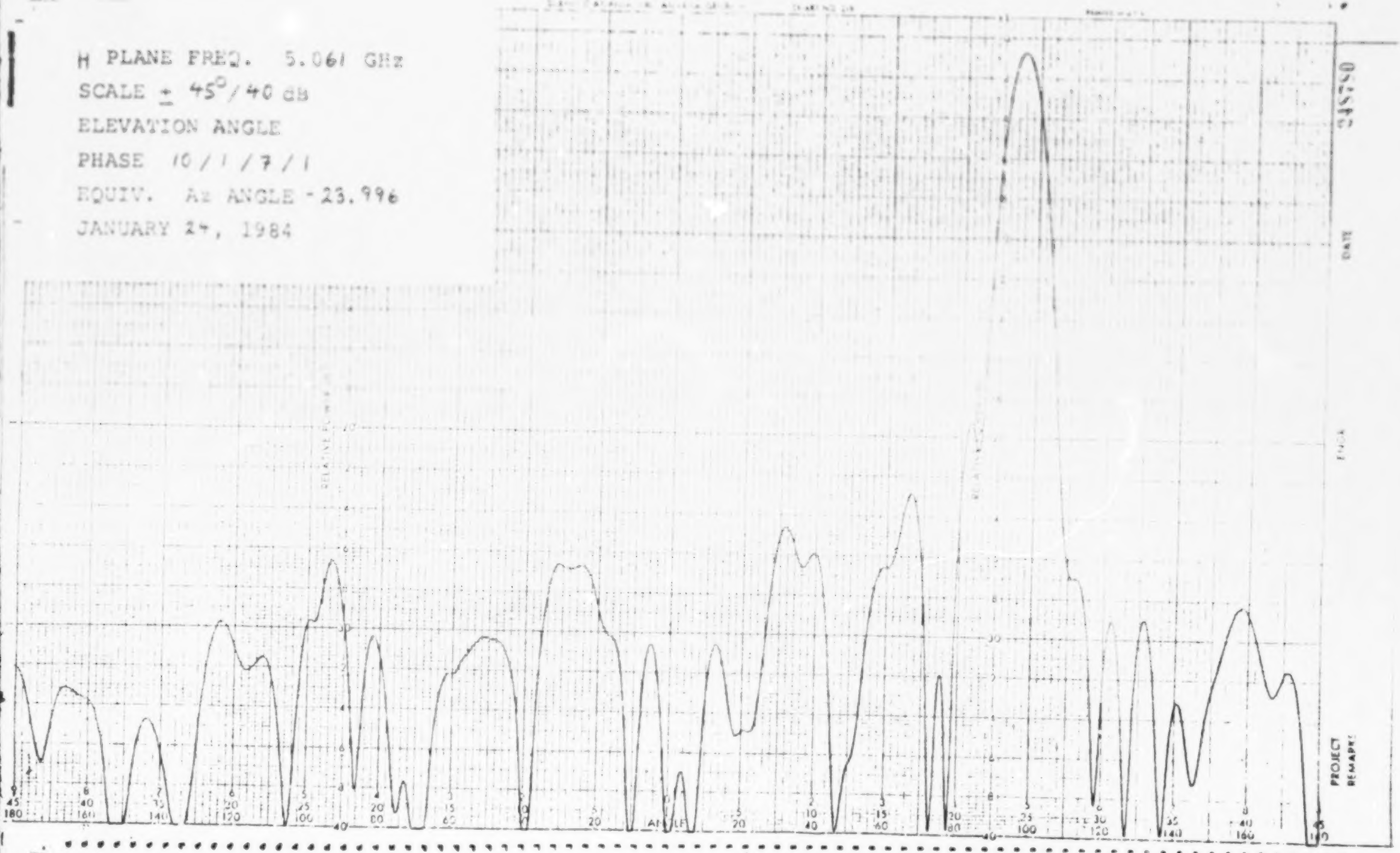


H PLANE FREQ. 5.061 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 10/0/15/12
EQUIV. Az ANGLE -22.010
JANUARY 24, 1984

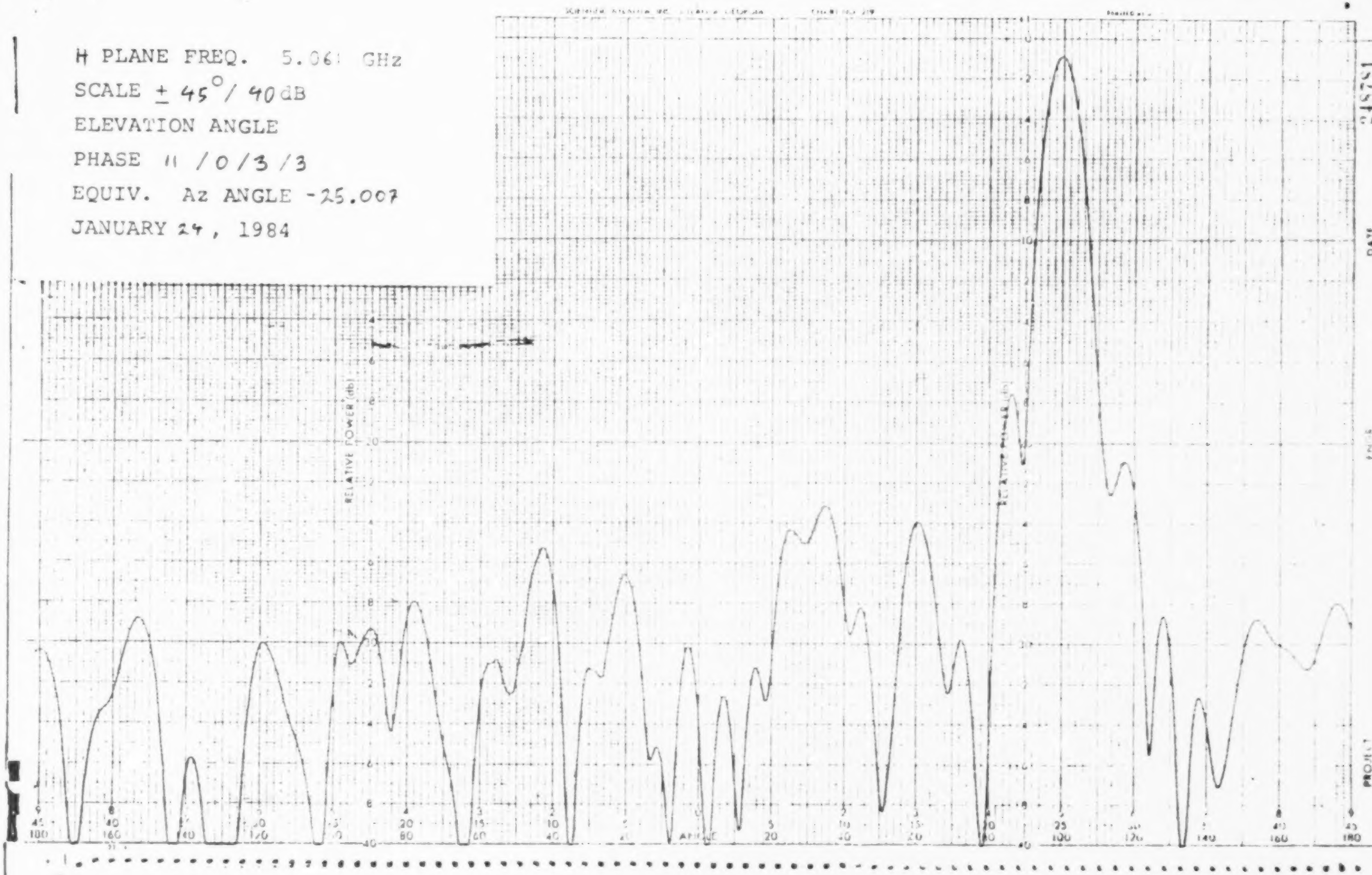
H PLANE FREQ. 5.061 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 10 / 1 / 3 / 8
EQUIV. Az ANGLE -23.005
JANUARY 24, 1984



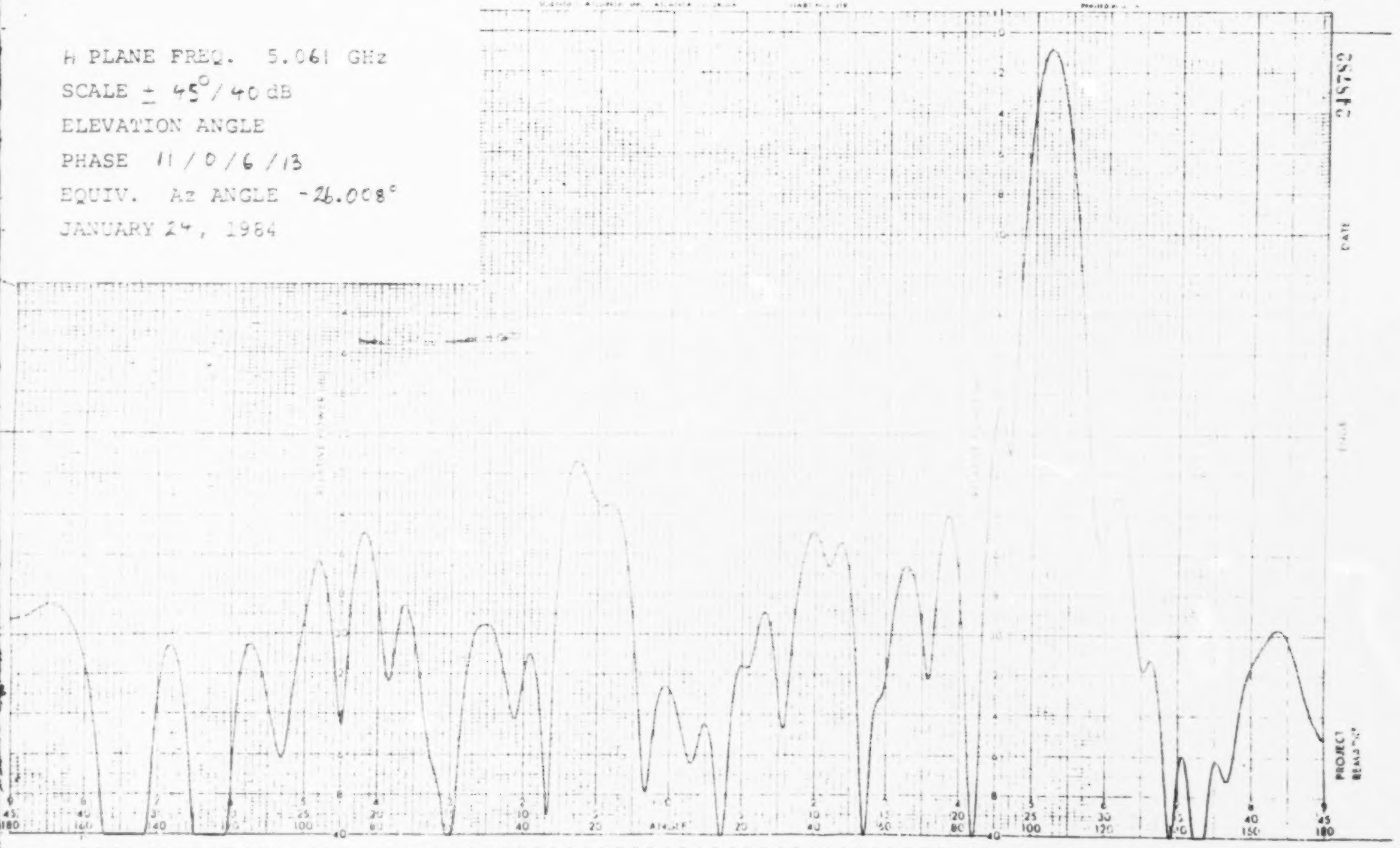
H PLANE FREQ. 5.061 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 10/1/7/1
EQUIV. Az ANGLE -23.996
JANUARY 24, 1984



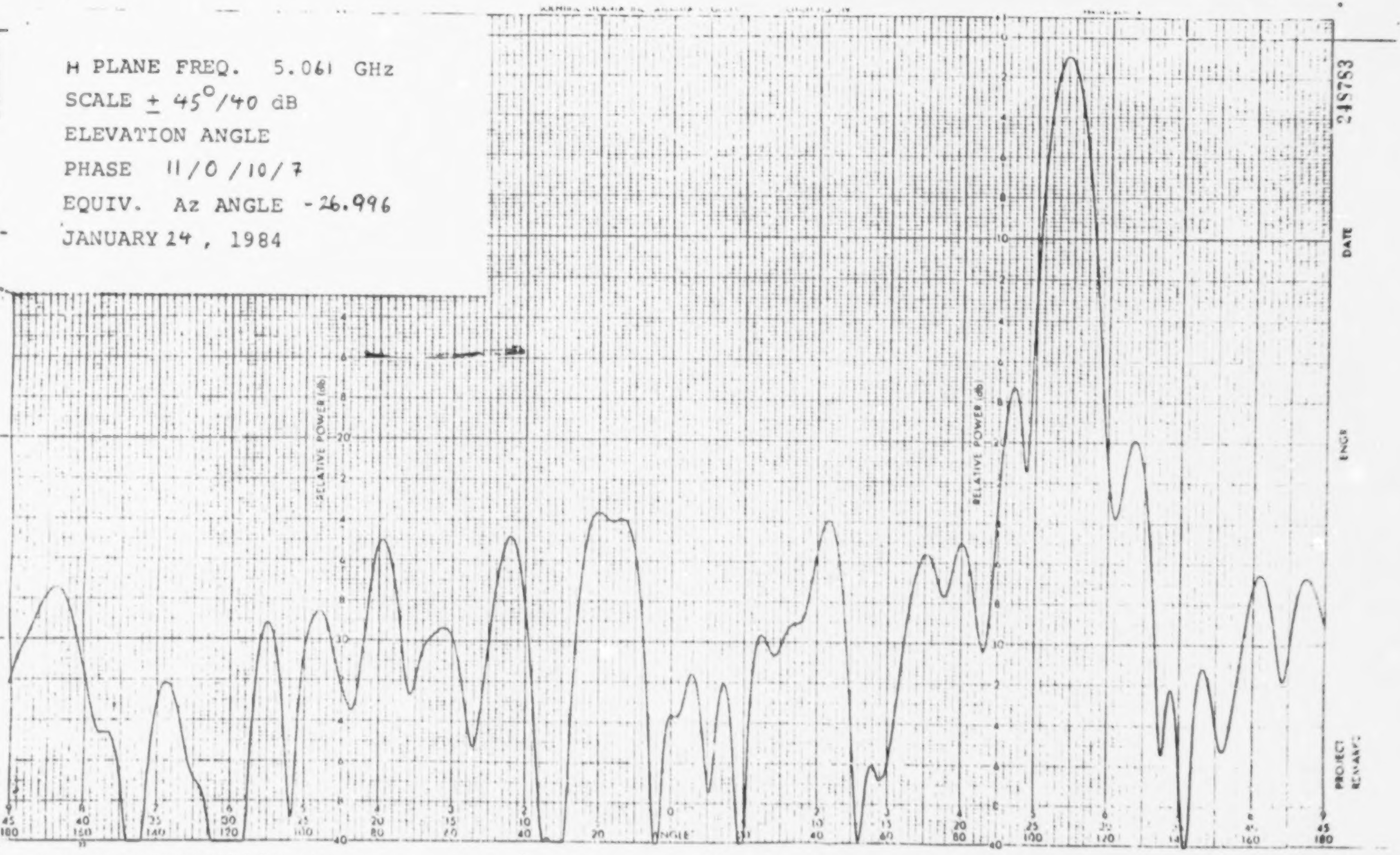
H PLANE FREQ. 5.061 GHz
SCALE ± 45°/ 40 dB
ELEVATION ANGLE
PHASE 11 /0/3/3
EQUIV. Az ANGLE -25.007
JANUARY 24, 1984



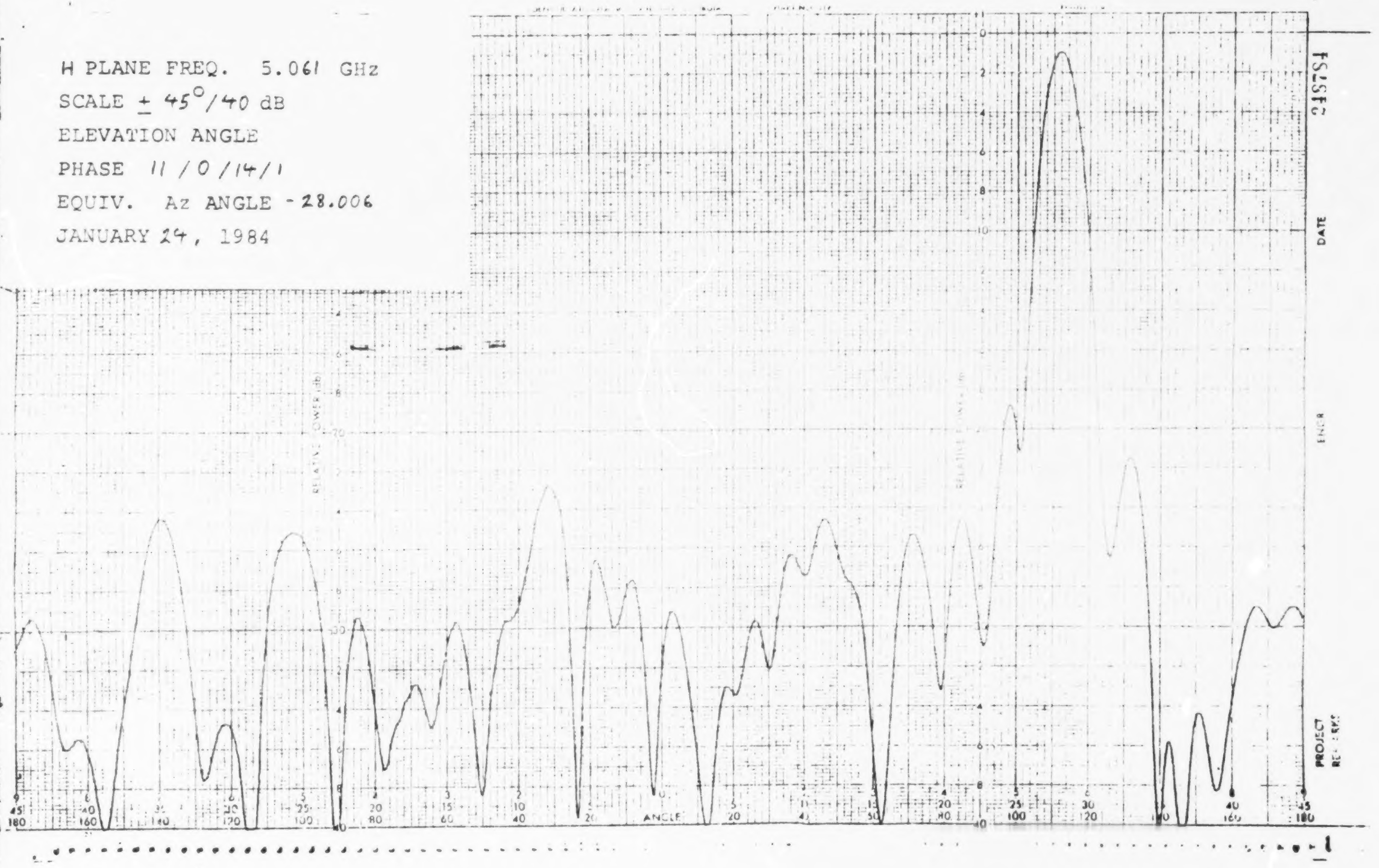
H PLANE FREQ. 5.061 GHz
SCALE ± 45°/ 40 dB
ELEVATION ANGLE
PHASE 11 / 0 / 6 / 13
EQUIV. Az ANGLE -26.008°
JANUARY 24, 1984



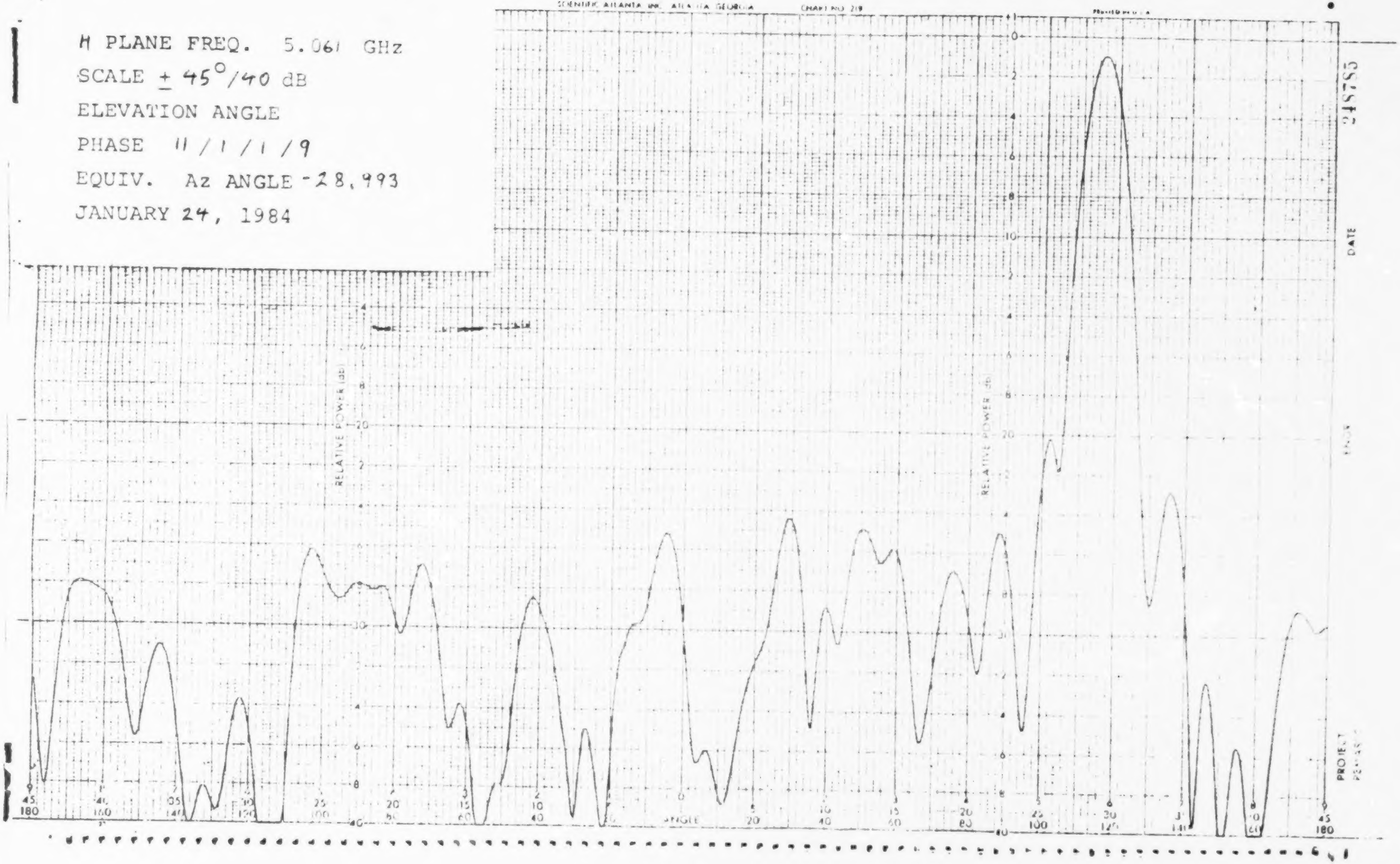
H PLANE FREQ. 5.061 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 11/0/10/7
EQUIV. Az ANGLE -26.996
JANUARY 24, 1984



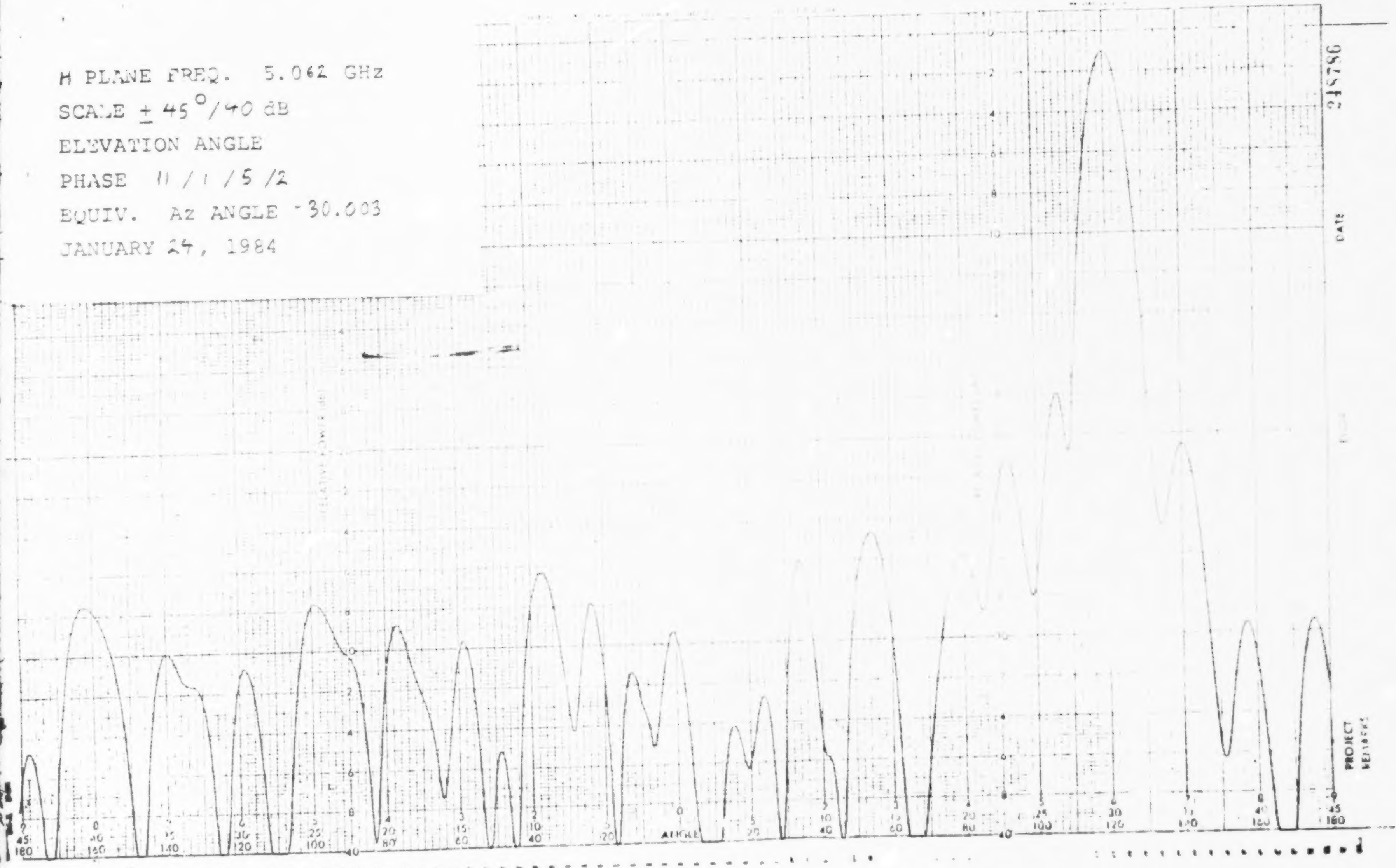
H PLANE FREQ. 5.061 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 11 / 0 / 14 / 1
EQUIV. Az ANGLE - 28.006
JANUARY 24, 1984



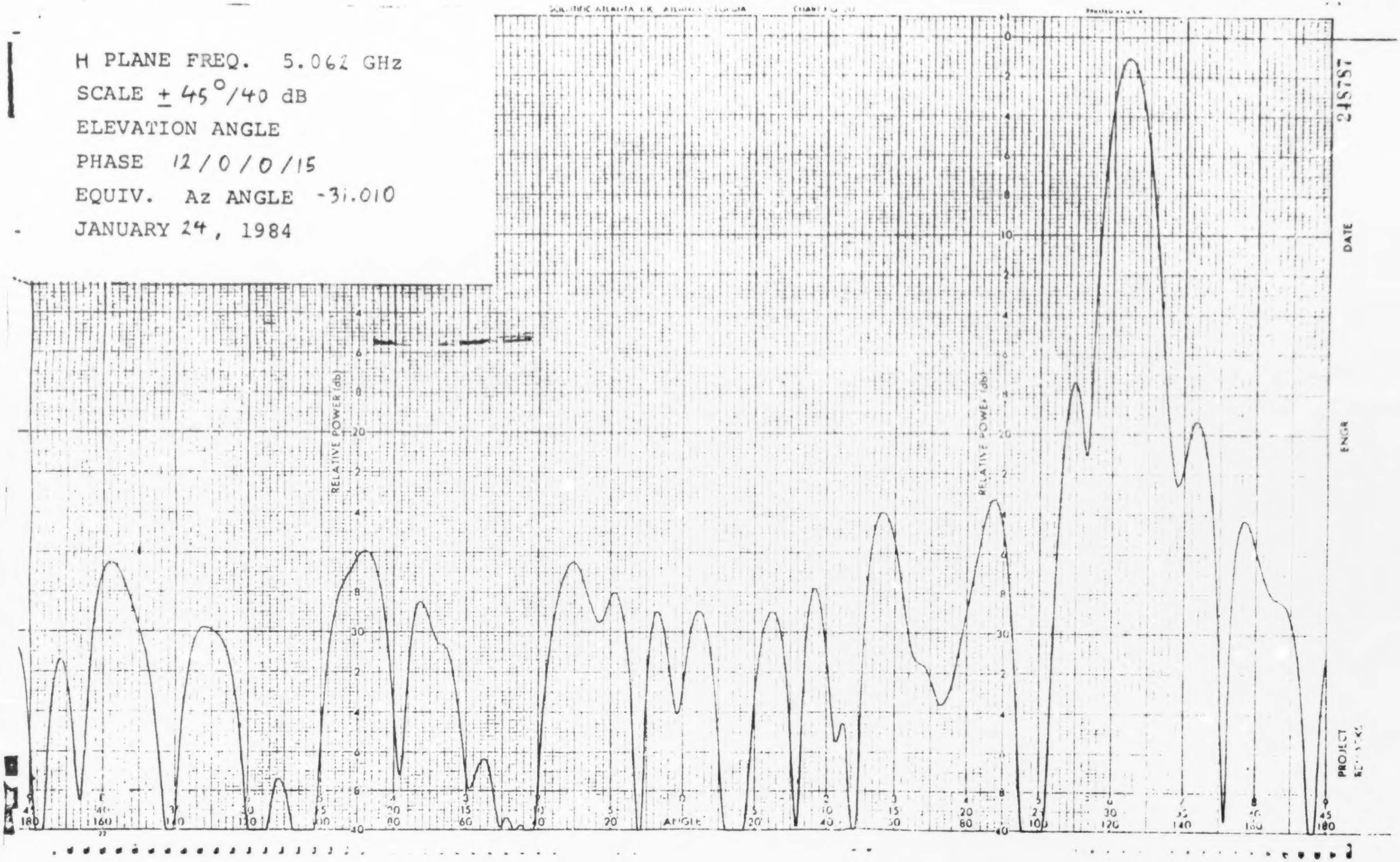
H PLANE FREQ. 5.061 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 11/1/1/9
EQUIV. Az ANGLE -28,993
JANUARY 24, 1984

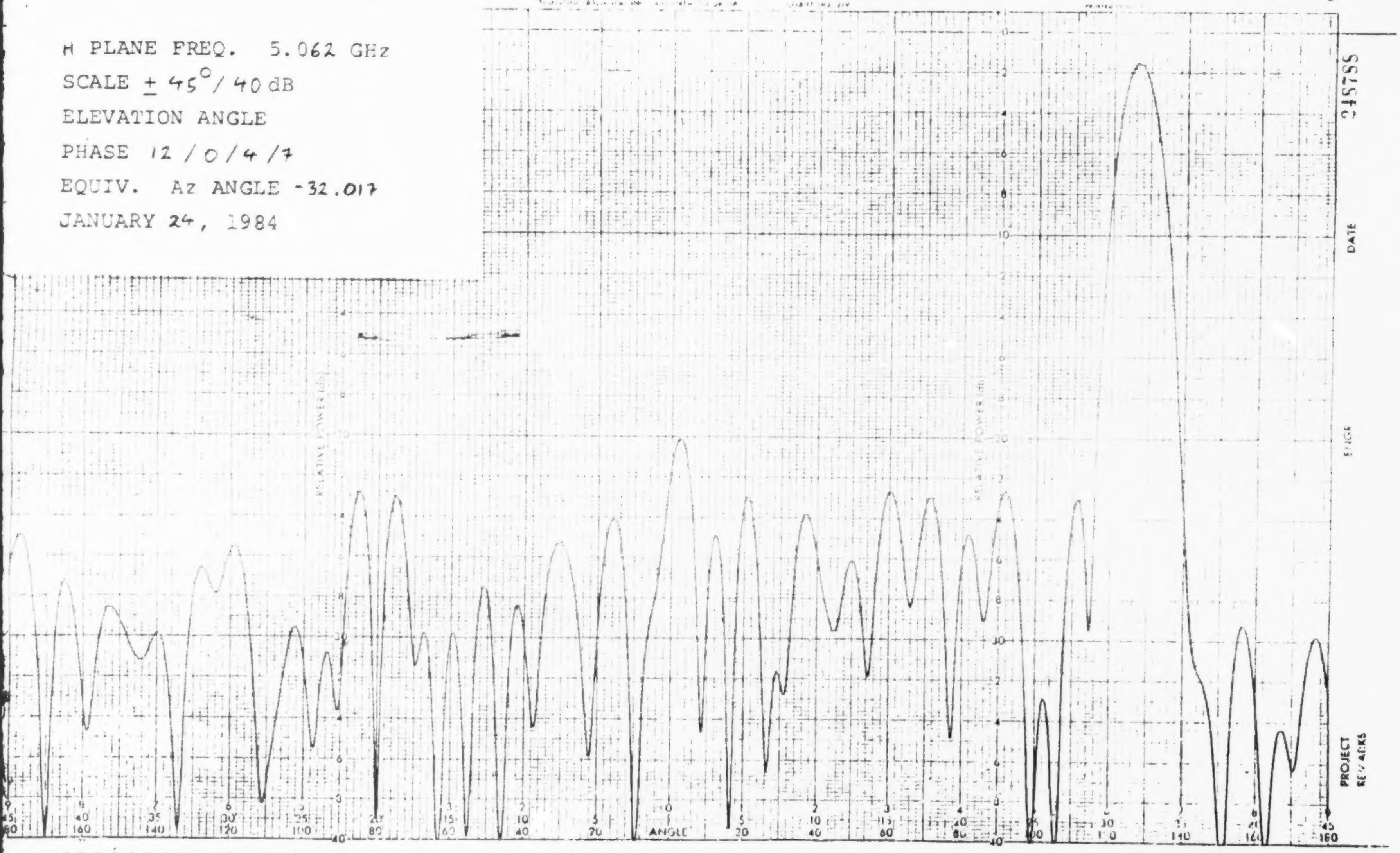


H PLANE FREQ. 5.062 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 11 / 1 / 5 / 2
EQUIV. Az ANGLE -30.003
JANUARY 24, 1984



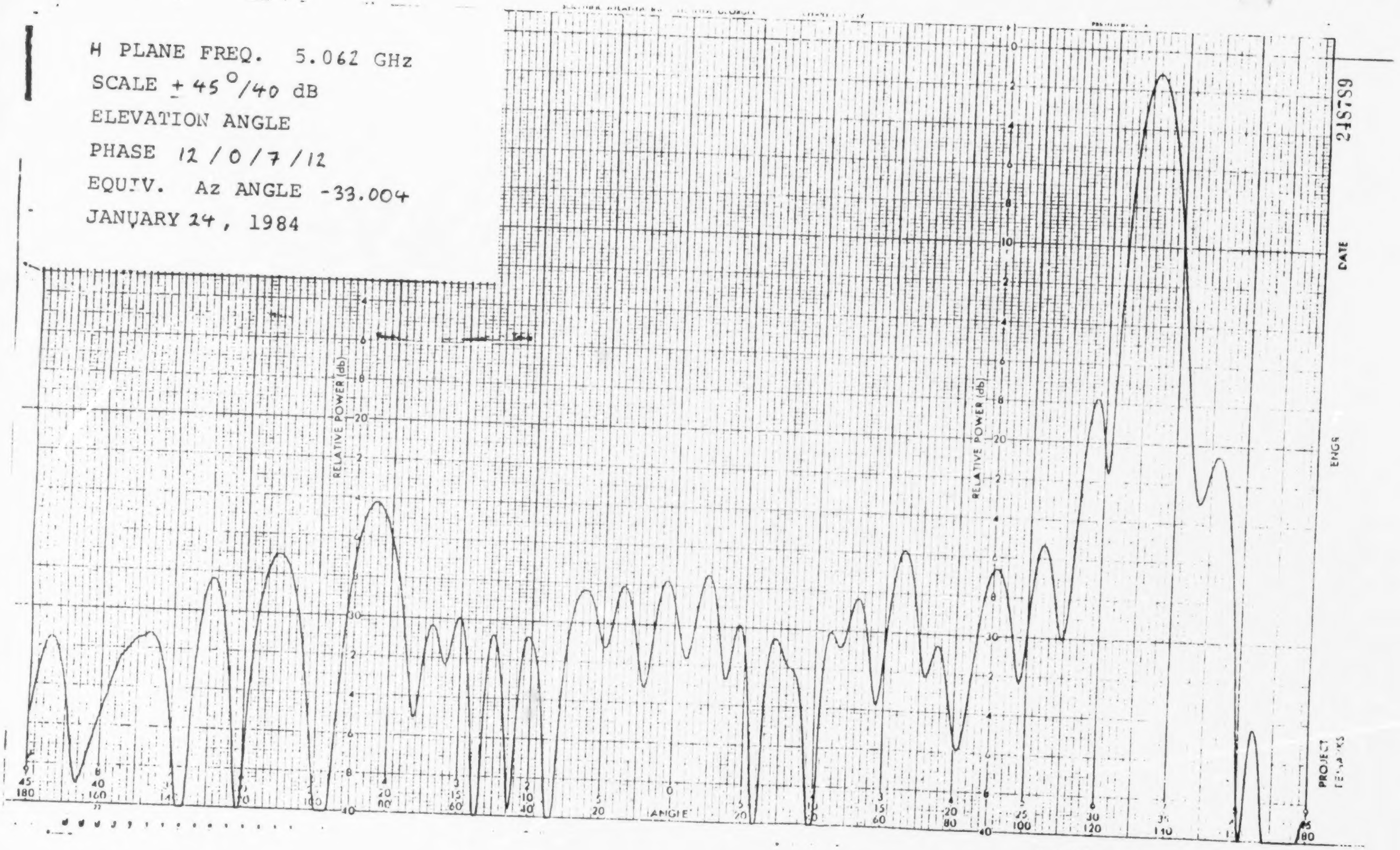
H PLANE FREQ. 5.062 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 12/0/0/15
EQUIV. Az ANGLE -31.010
JANUARY 24, 1984



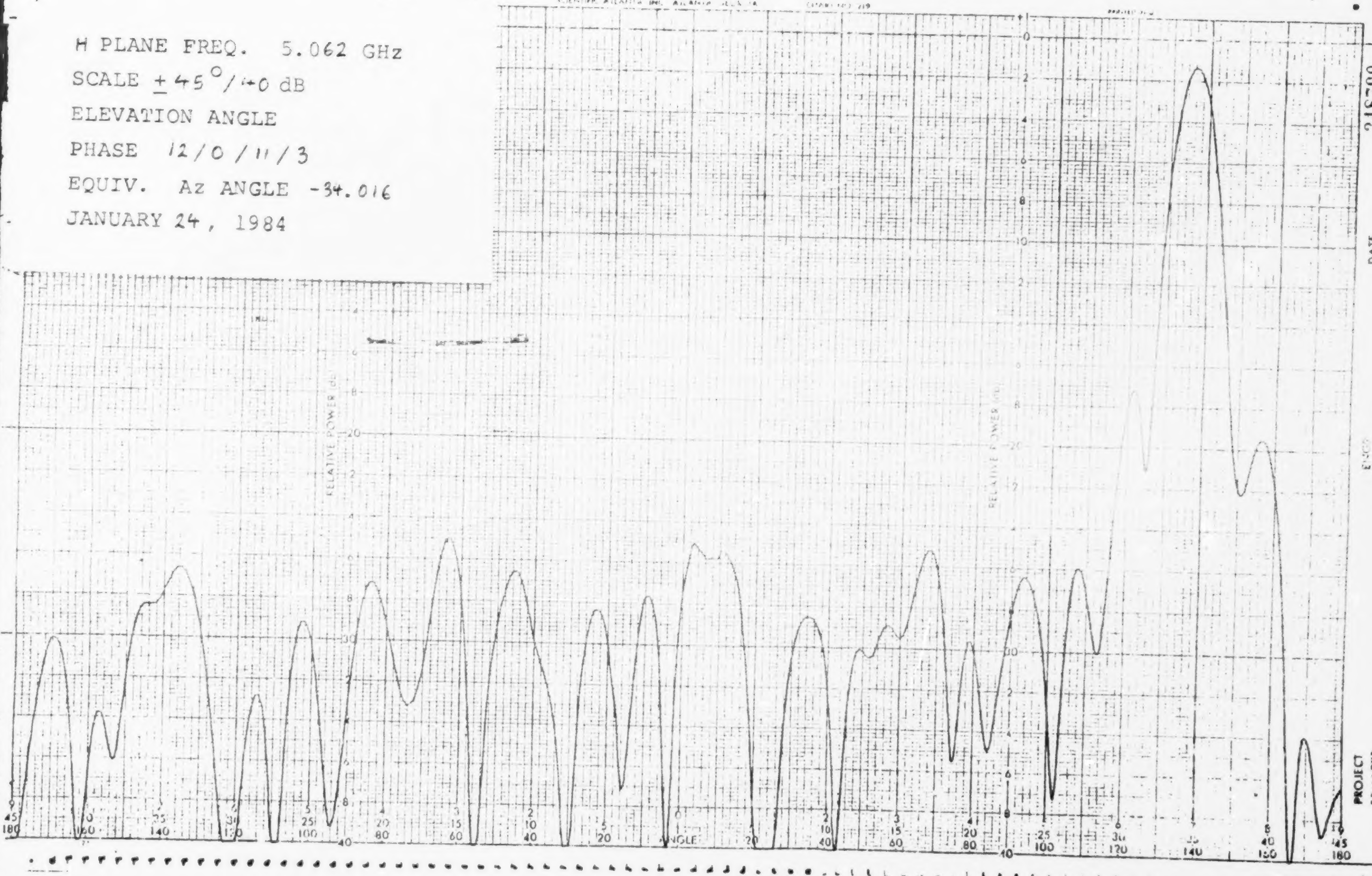


H PLANE FREQ. 5.062 GHz
SCALE ± 45°/ 40 dB
ELEVATION ANGLE
PHASE 12 / 0 / 4 / 7
EQUIV. Az ANGLE -32.017
JANUARY 24, 1984

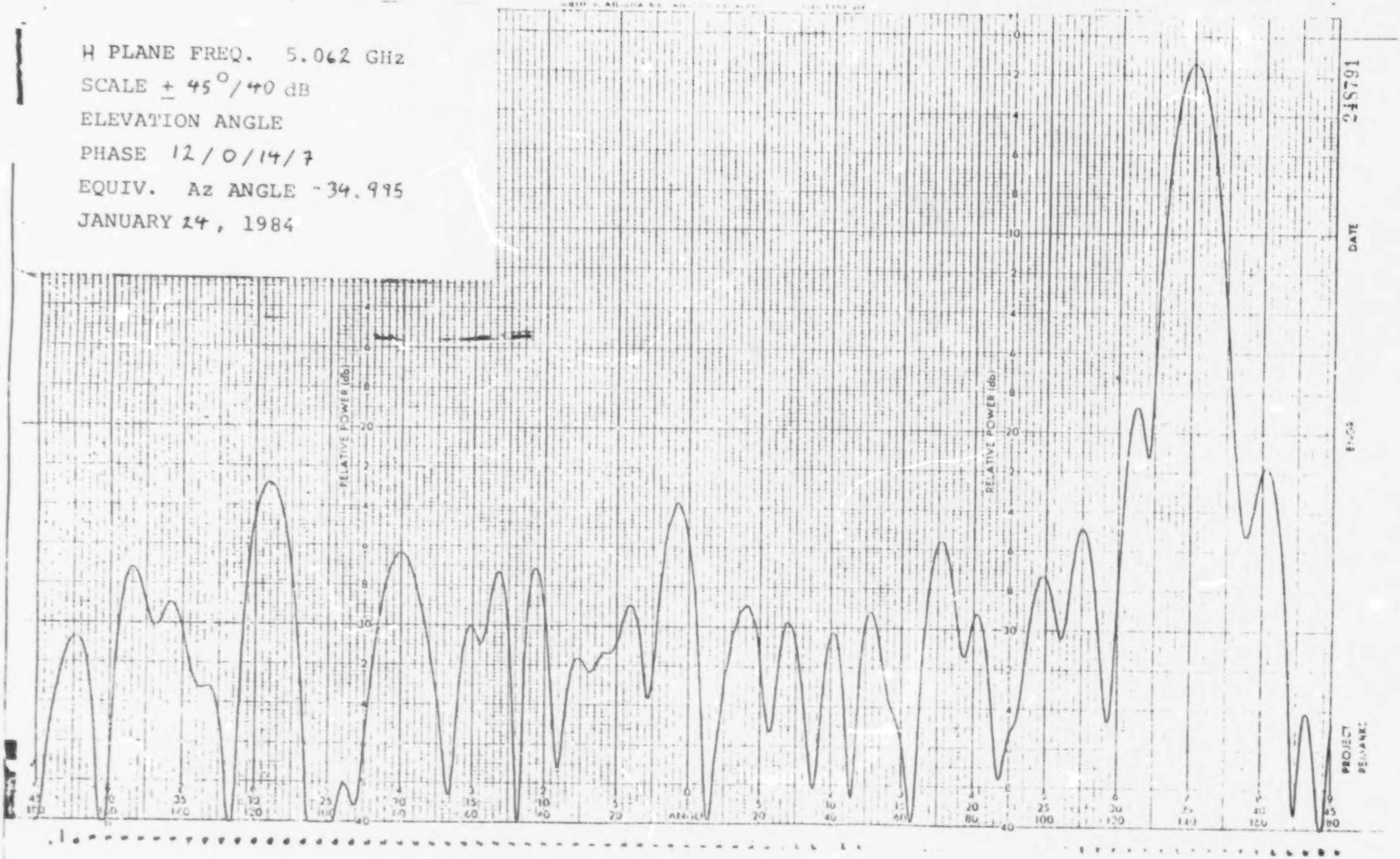
H PLANE FREQ. 5.062 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 12 / 0 / 7 / 12
EQUIV. Az ANGLE -33.004
JANUARY 24, 1984

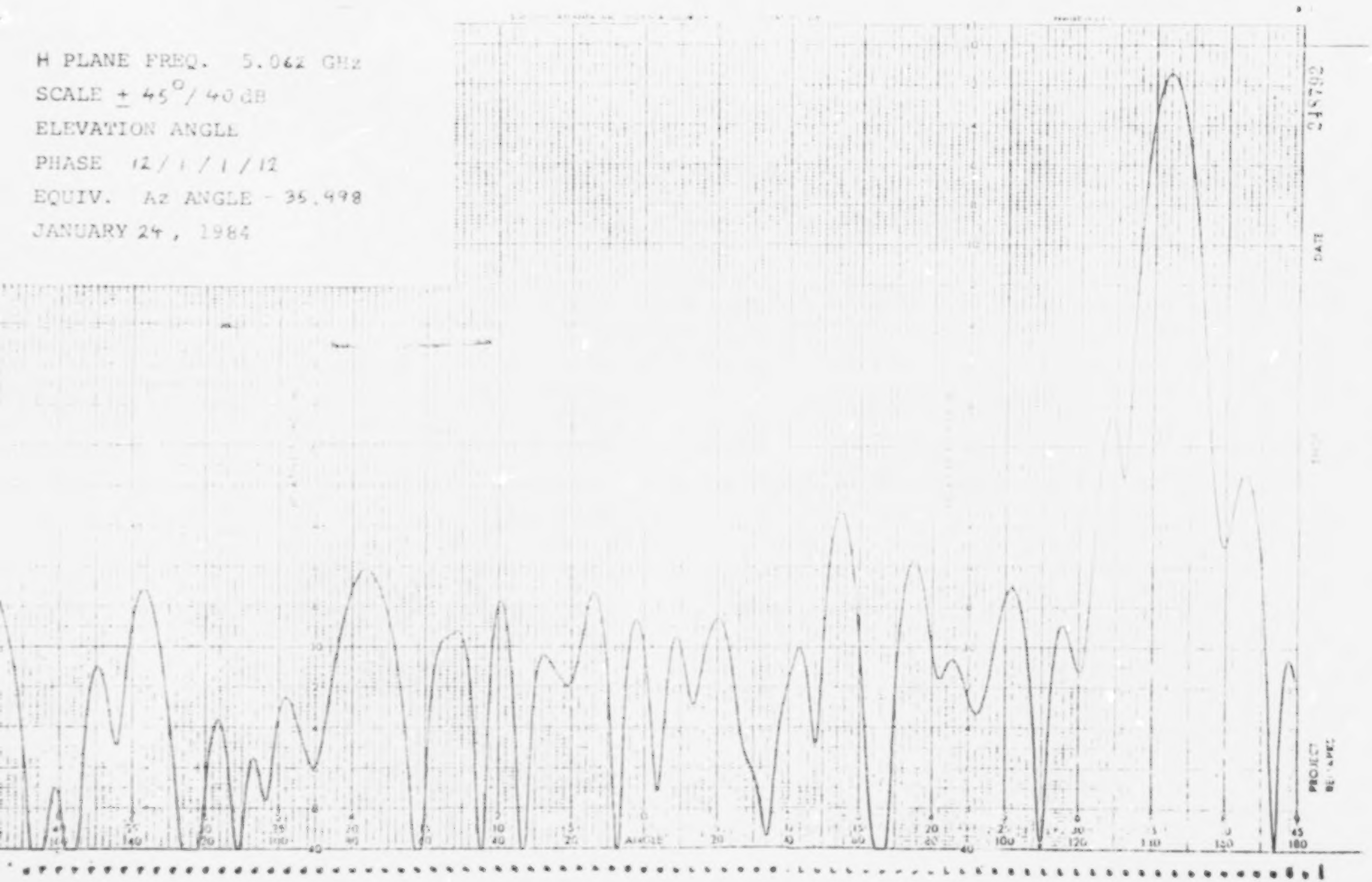


H PLANE FREQ. 5.062 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 12/0/11/3
EQUIV. Az ANGLE -34.016
JANUARY 24, 1984



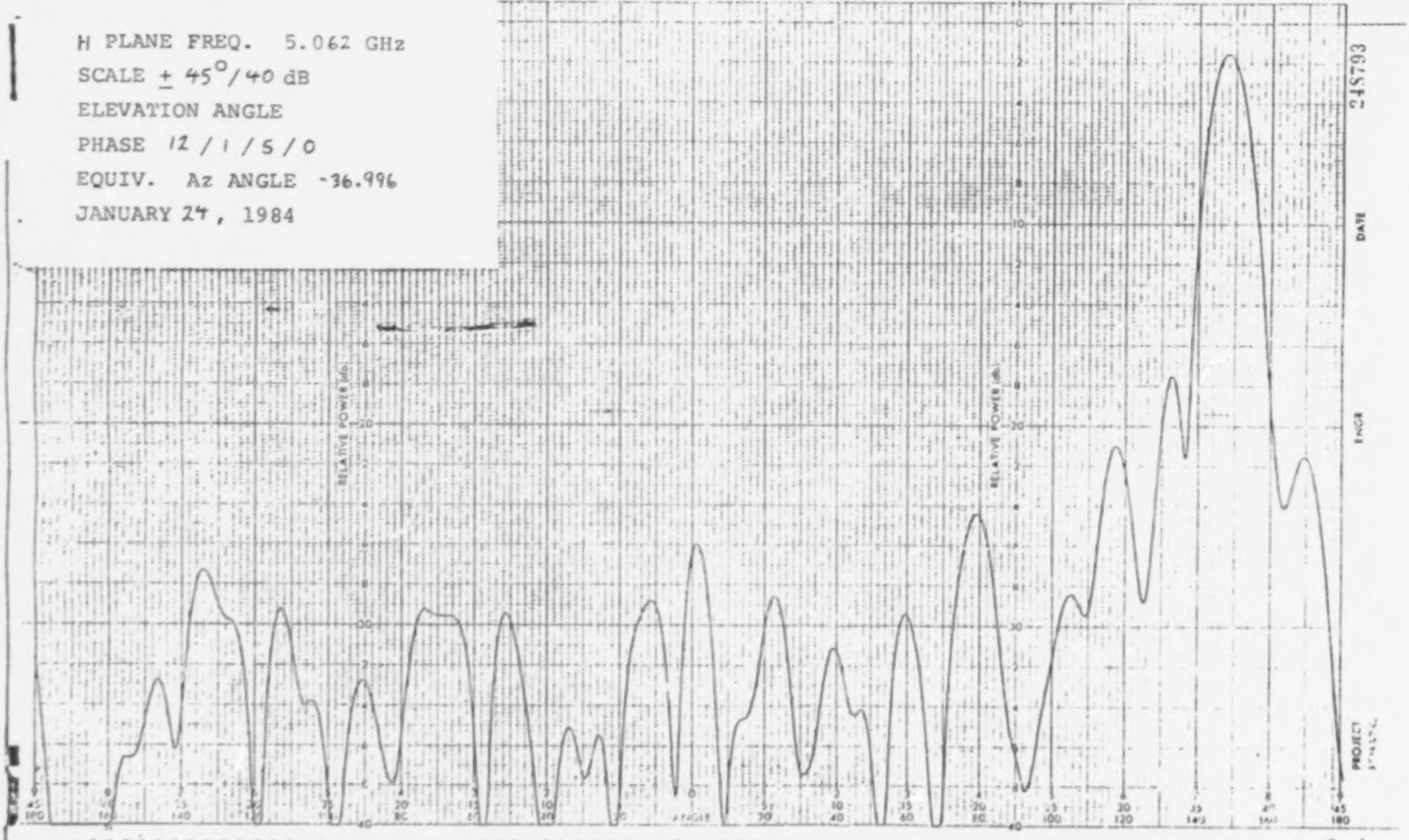
H PLANE FREQ. 5.062 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 12/0/14/7
EQUIV. Az ANGLE -34.995
JANUARY 24, 1984



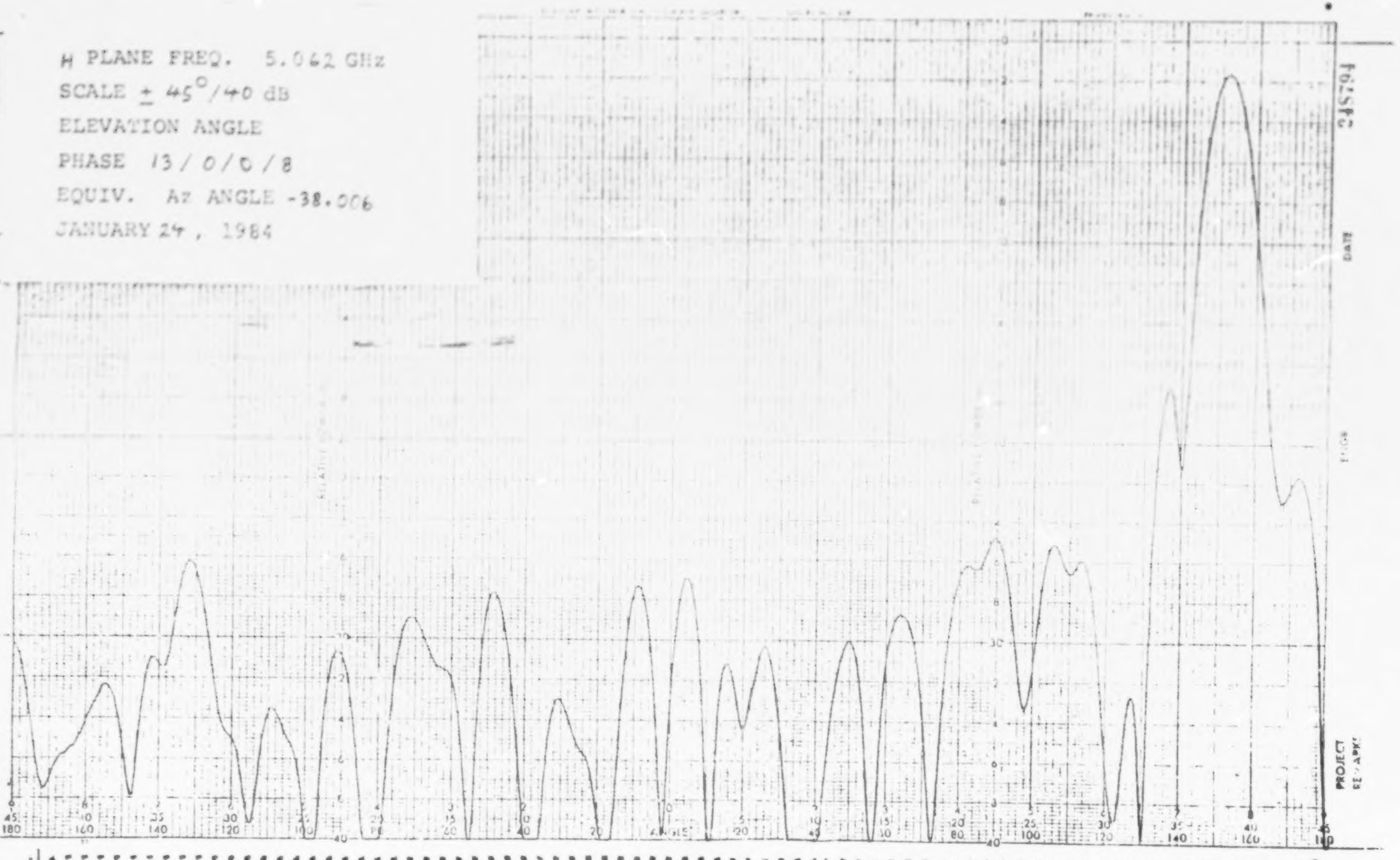


H PLANE FREQ. 5.062 GHz
SCALE ± 45°/ 40 dB
ELEVATION ANGLE
PHASE 12 / 1 / 1 / 12
EQUIV. Az ANGLE - 35.998
JANUARY 24 , 1984

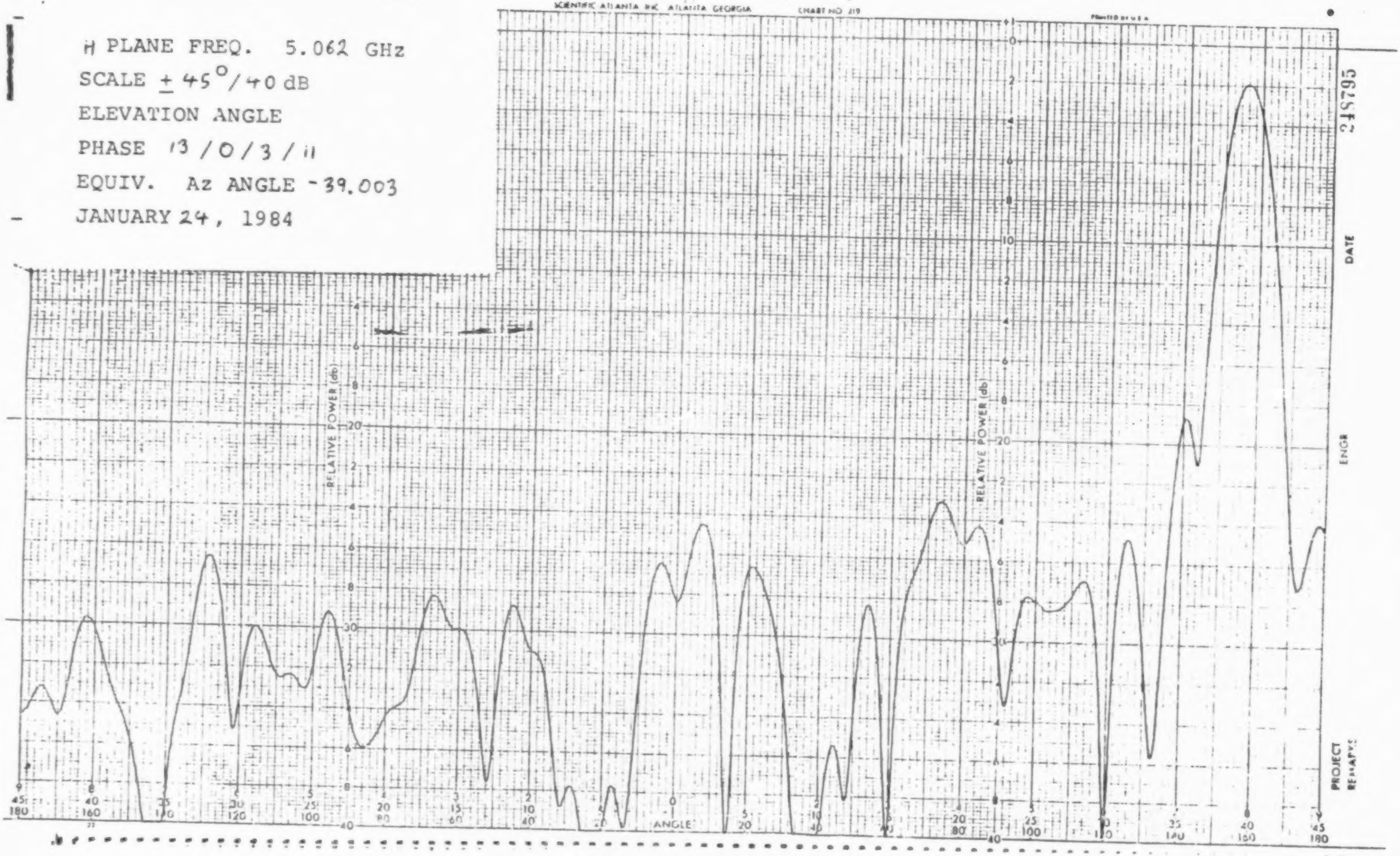
H PLANE FREQ. 5.062 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 12 / 1 / 5 / 0
EQUIV. Az ANGLE -36.996
JANUARY 24, 1984



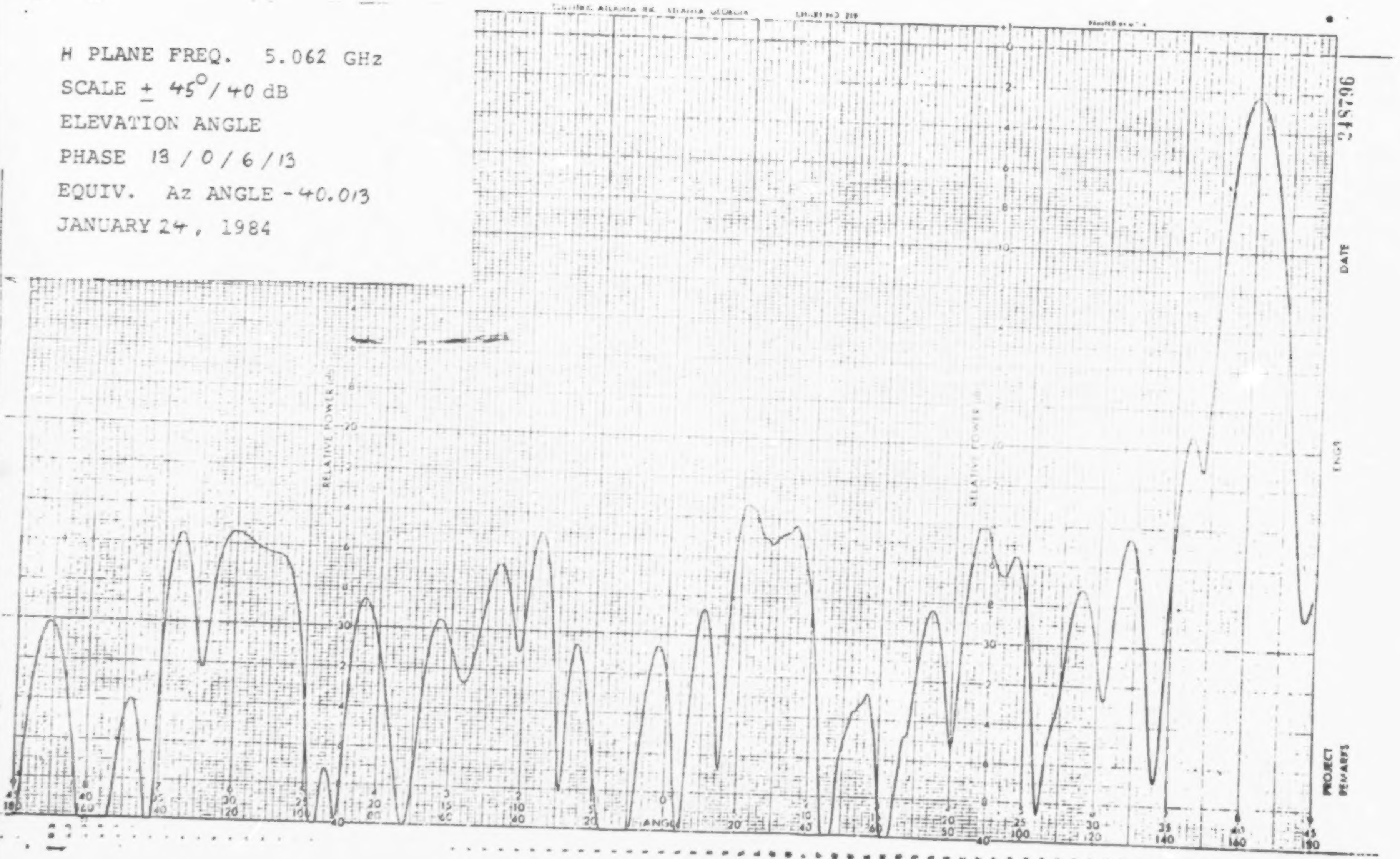
H PLANE FREQ. 5.062 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 13 / 0 / 0 / 8
EQUIV. Az ANGLE -38.006
JANUARY 24, 1984



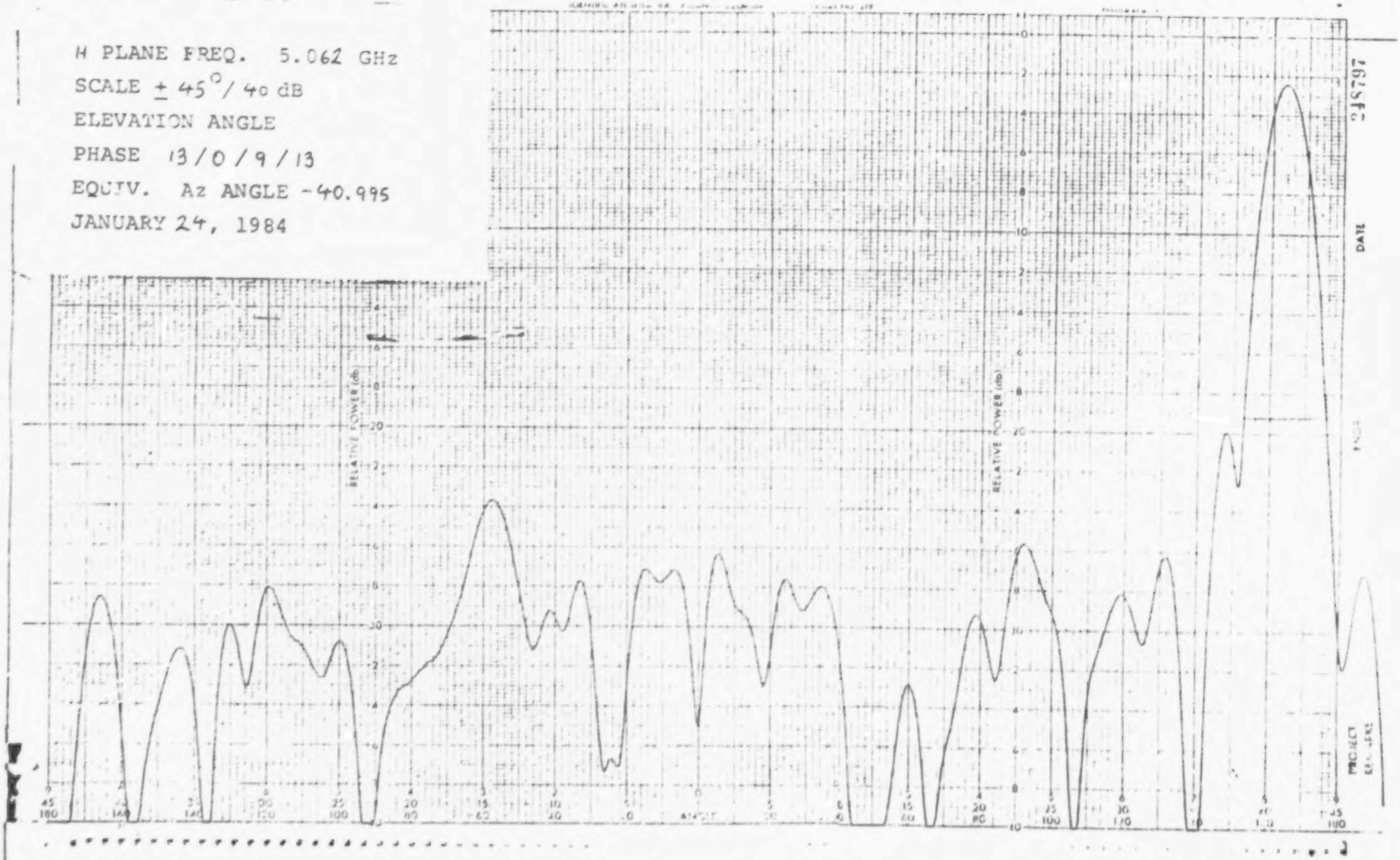
H PLANE FREQ. 5.062 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 13 / 0 / 3 / 11
EQUIV. Az ANGLE -39.003
JANUARY 24, 1984



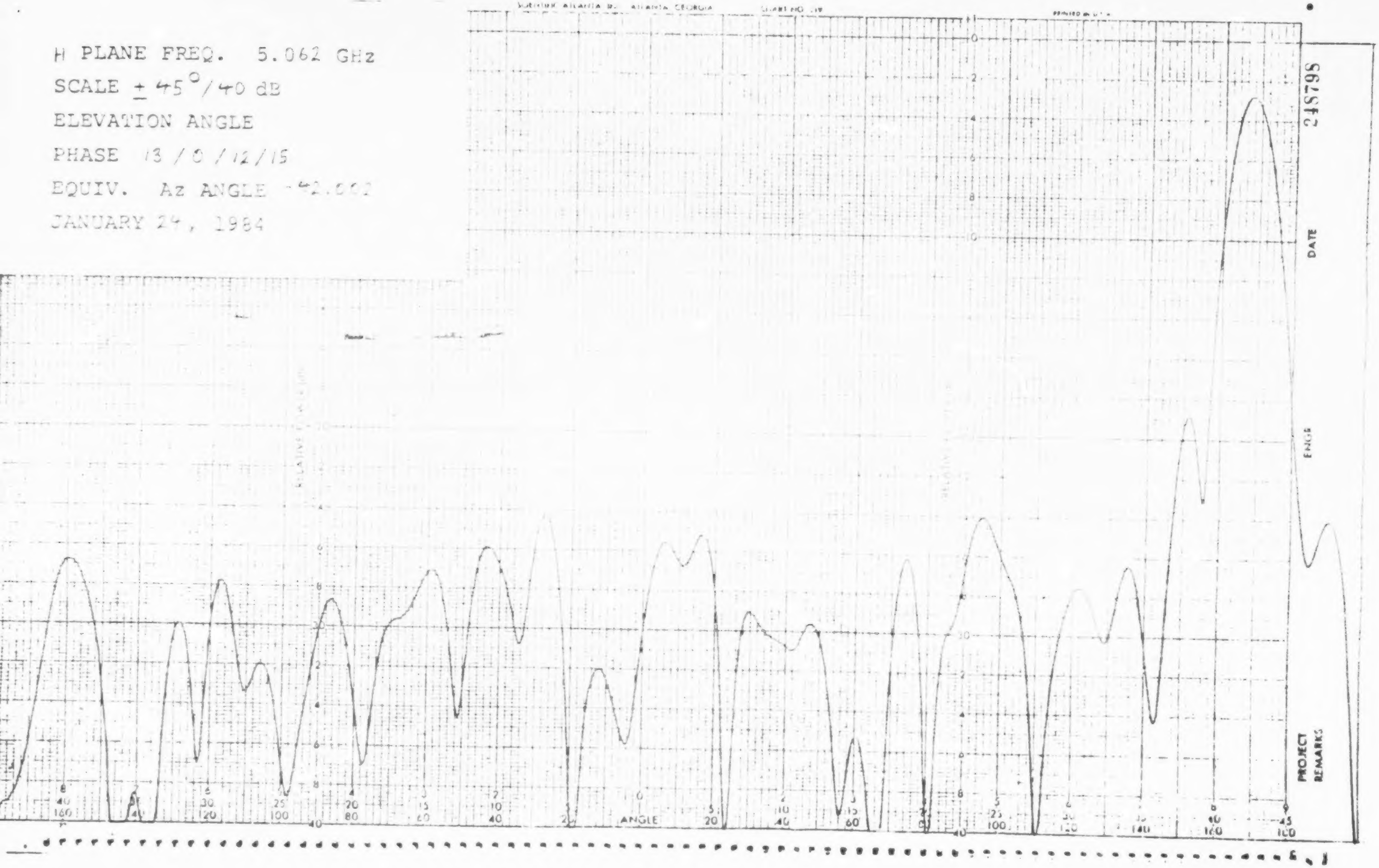
H PLANE FREQ. 5.062 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 13/0/6/13
EQUIV. Az ANGLE -40.013
JANUARY 24, 1984



H PLANE FREQ. 5.062 GHz
SCALE ± 45°/ 40 dB
ELEVATION ANGLE
PHASE 13/0/9/13
EQUIV. Az ANGLE -40.995
JANUARY 24, 1984

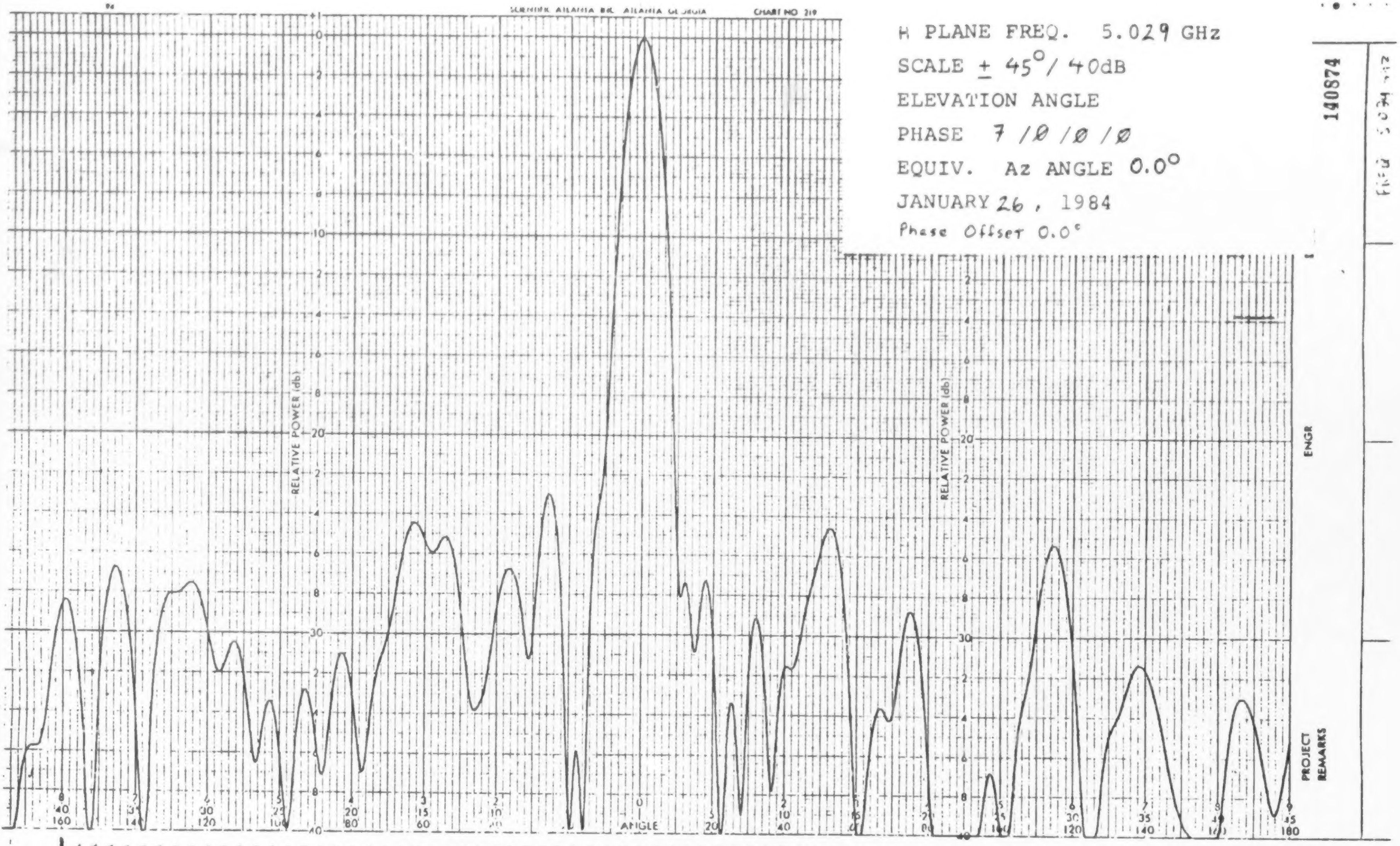


H PLANE FREQ. 5.062 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 13 / 0 / 12/15
EQUIV. Az ANGLE -42.002
JANUARY 24, 1984

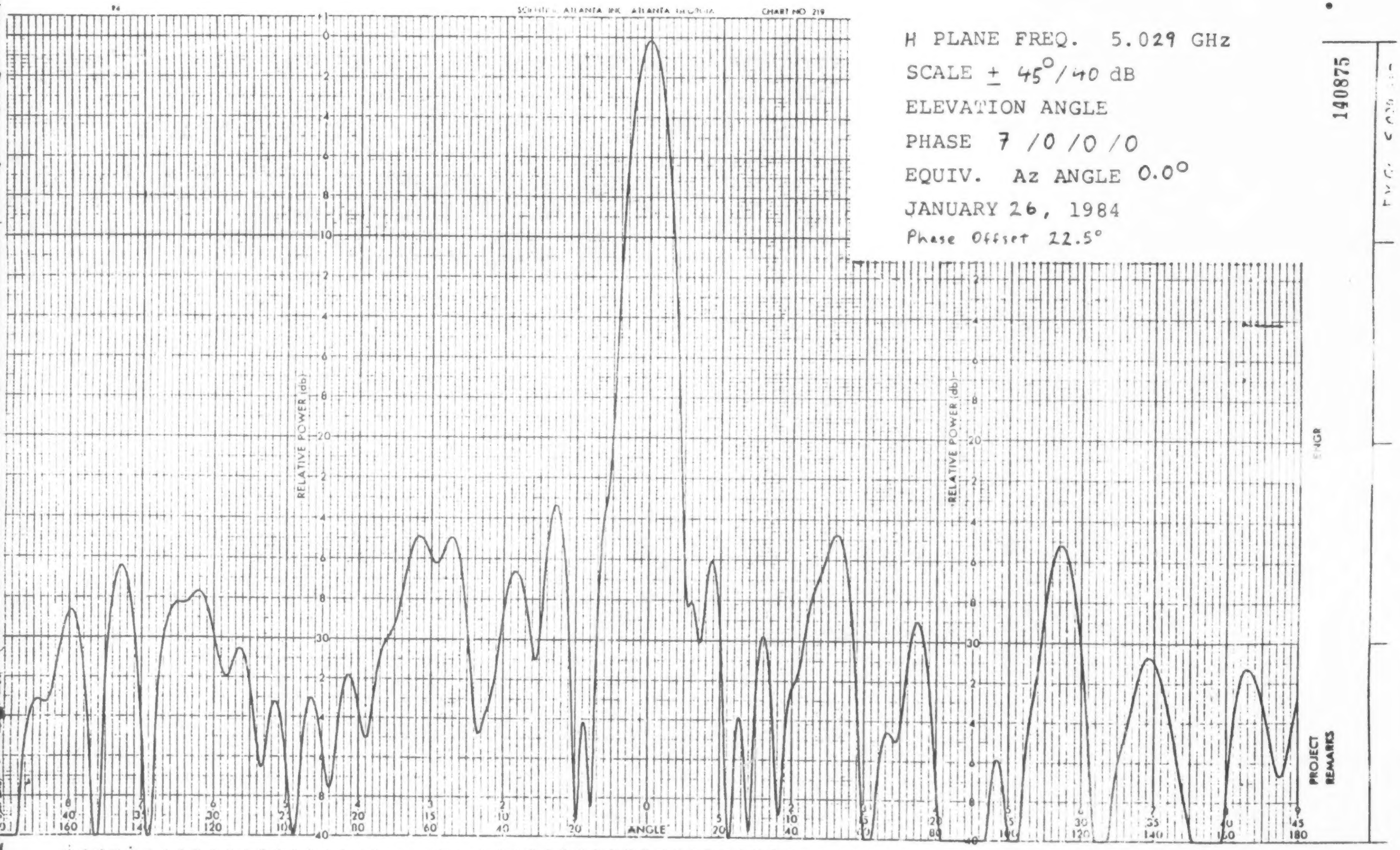


APPENDIX 3

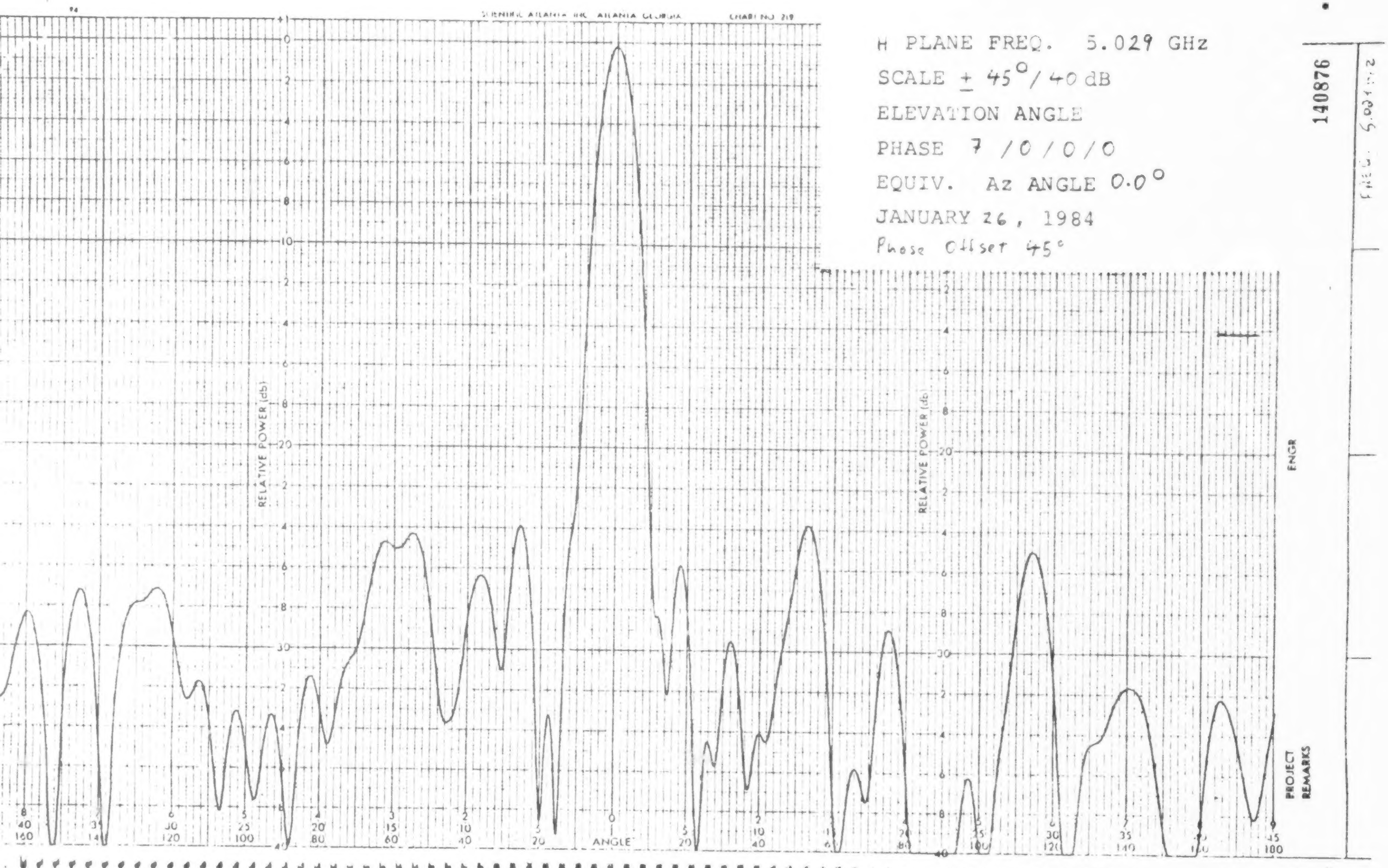
Azimuth Scans
for
phase offsets of 22.5°, 45°, 90° and 180°
at 0° azimuth angle for frequencies 5030, 5060, 5090



H PLANE FREQ. 5.029 GHz
SCALE ± 45°/ 40dB
ELEVATION ANGLE
PHASE 7 /0 /0 /0
EQUIV. Az ANGLE 0.0°
JANUARY 26 , 1984
Phase Offset 0.0°



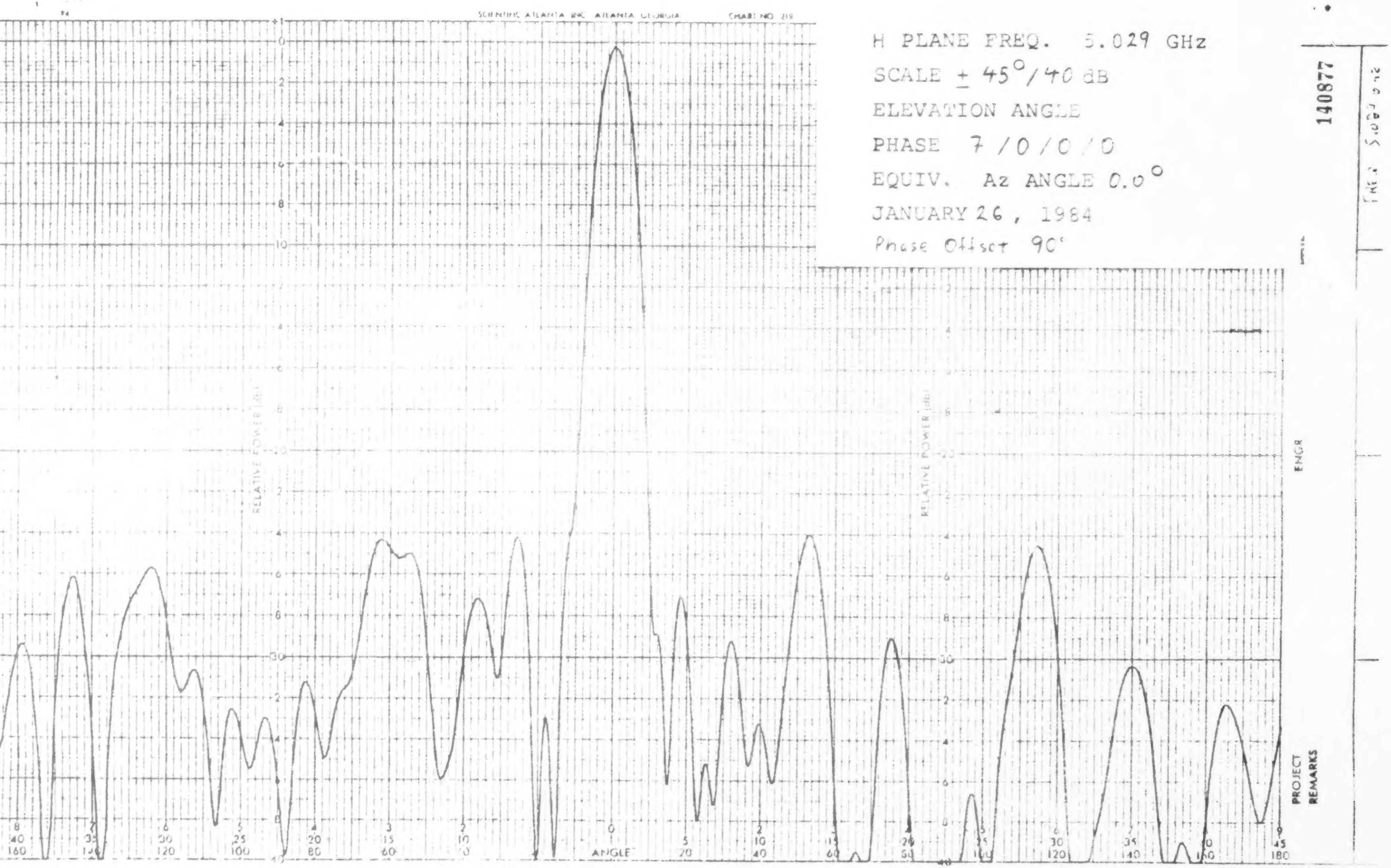
H PLANE FREQ. 5.029 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 7 /0 /0 /0
EQUIV. Az ANGLE 0.0°
JANUARY 26, 1984
Phase Offset 22.5°



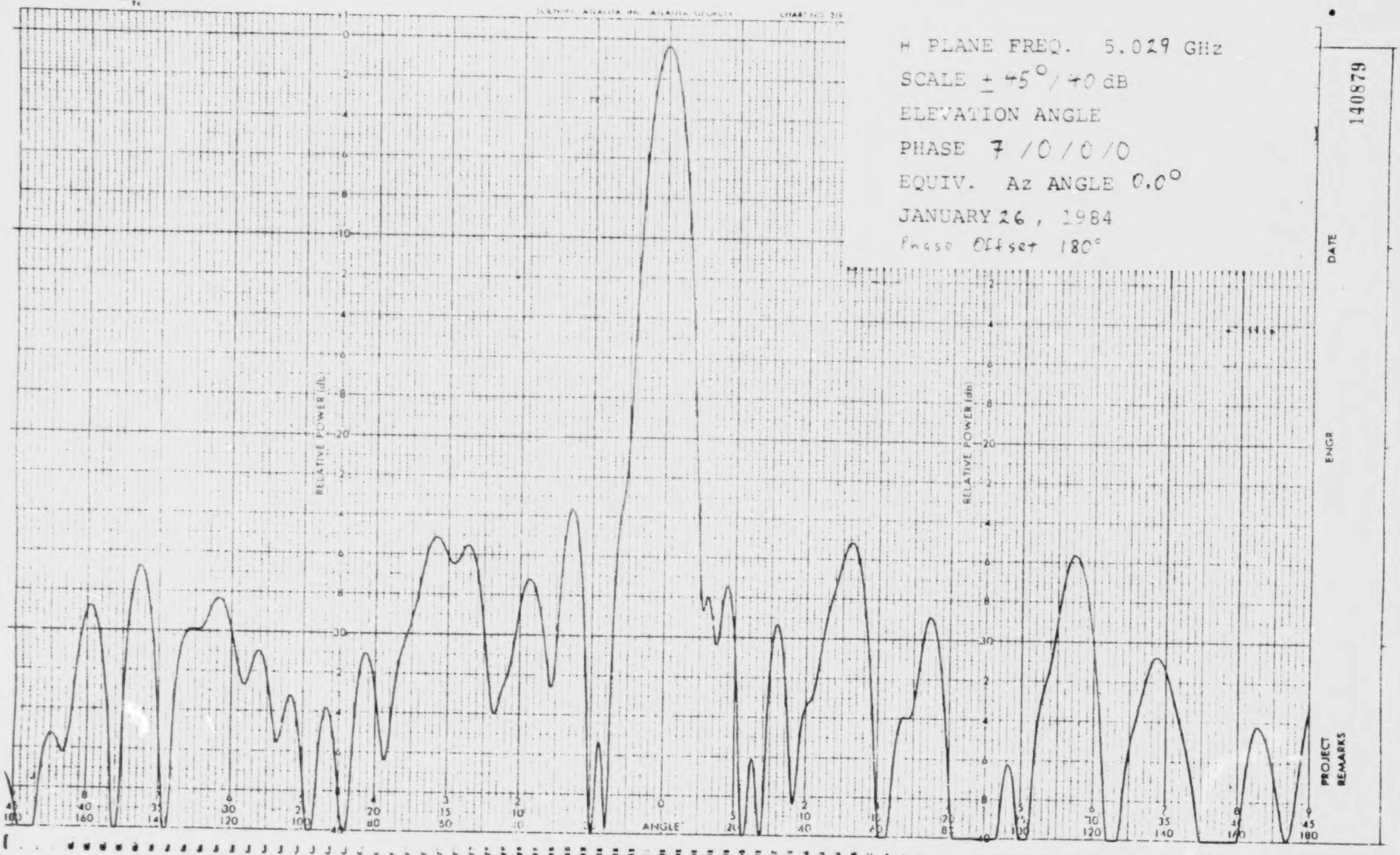
H PLANE FREQ. 5.029 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 7 /0/0/0
EQUIV. Az ANGLE 0.0°
JANUARY 26, 1984
Phase Offset 45°

140876

FREQ. 5.029 GHz

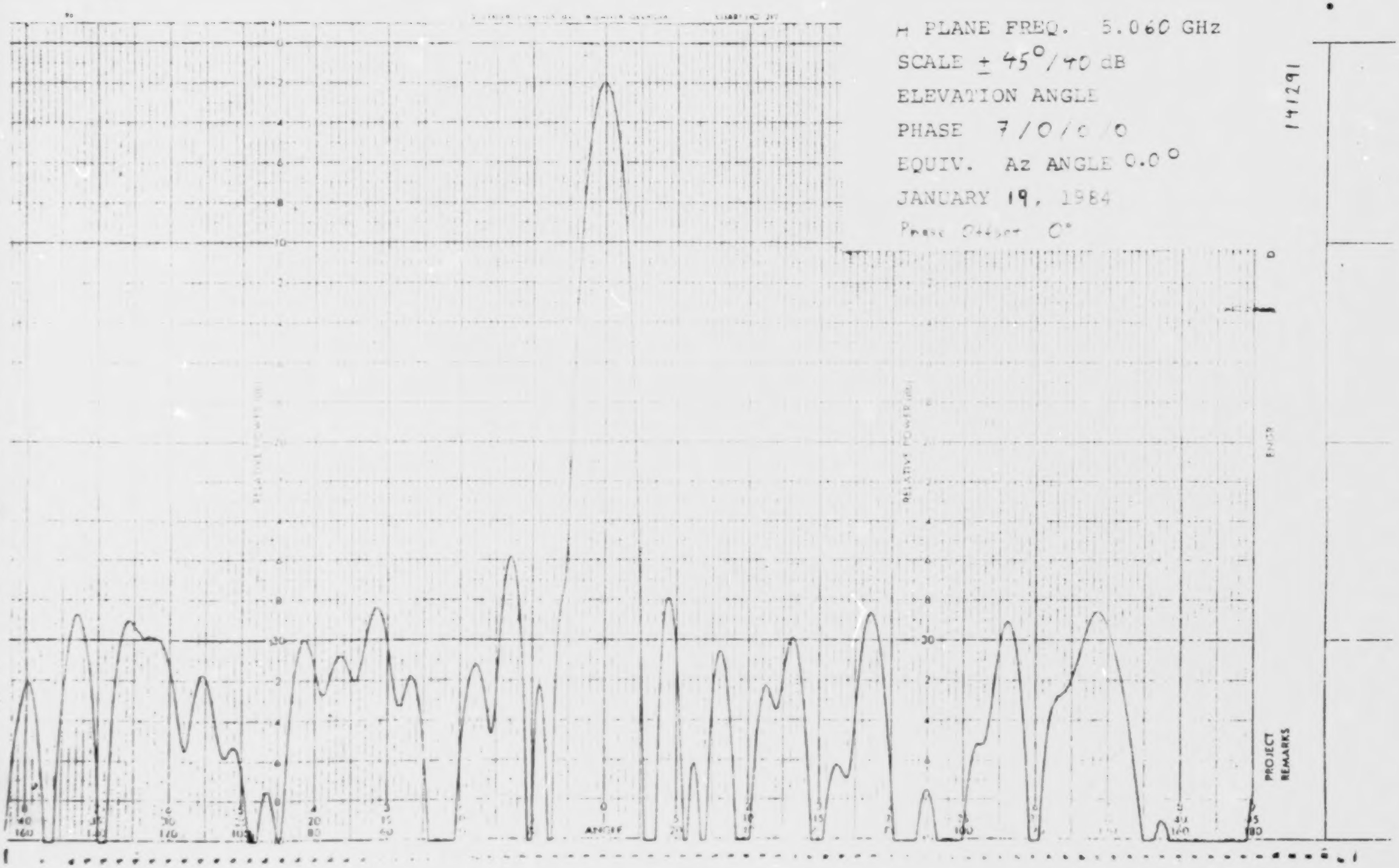


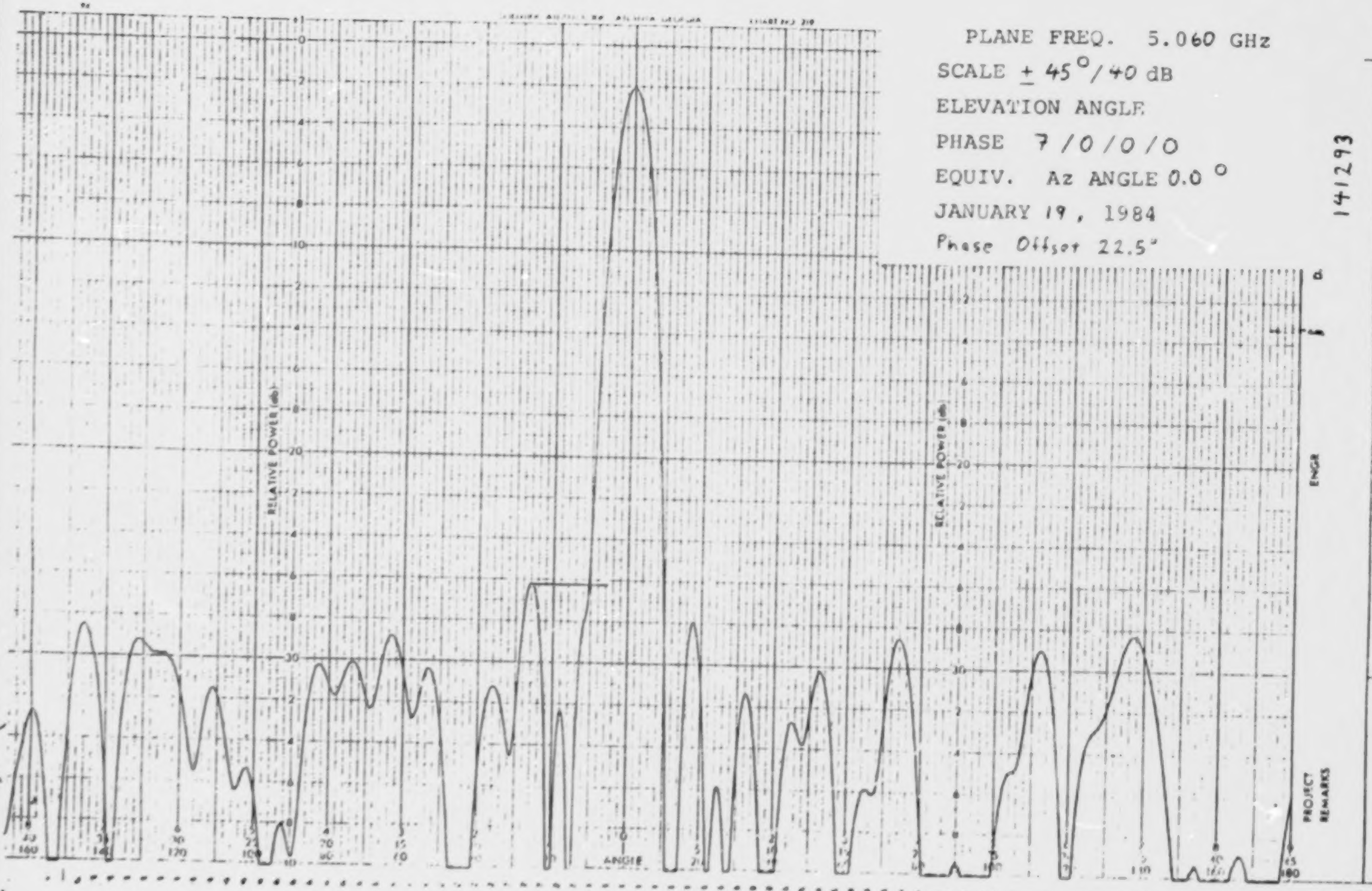
H PLANE FREQ. 5.029 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 7 / 0 / 0 / 0
EQUIV. Az ANGLE 0.0°
JANUARY 26, 1984
Phase Offset 90°



H PLANE FREQ. 5.029 GHz
SCALE ± 45°/ 40 dB
ELEVATION ANGLE
PHASE 7 /0/0/0
EQUIV. Az ANGLE 0.0°
JANUARY 26, 1984
Phase Offset 180°

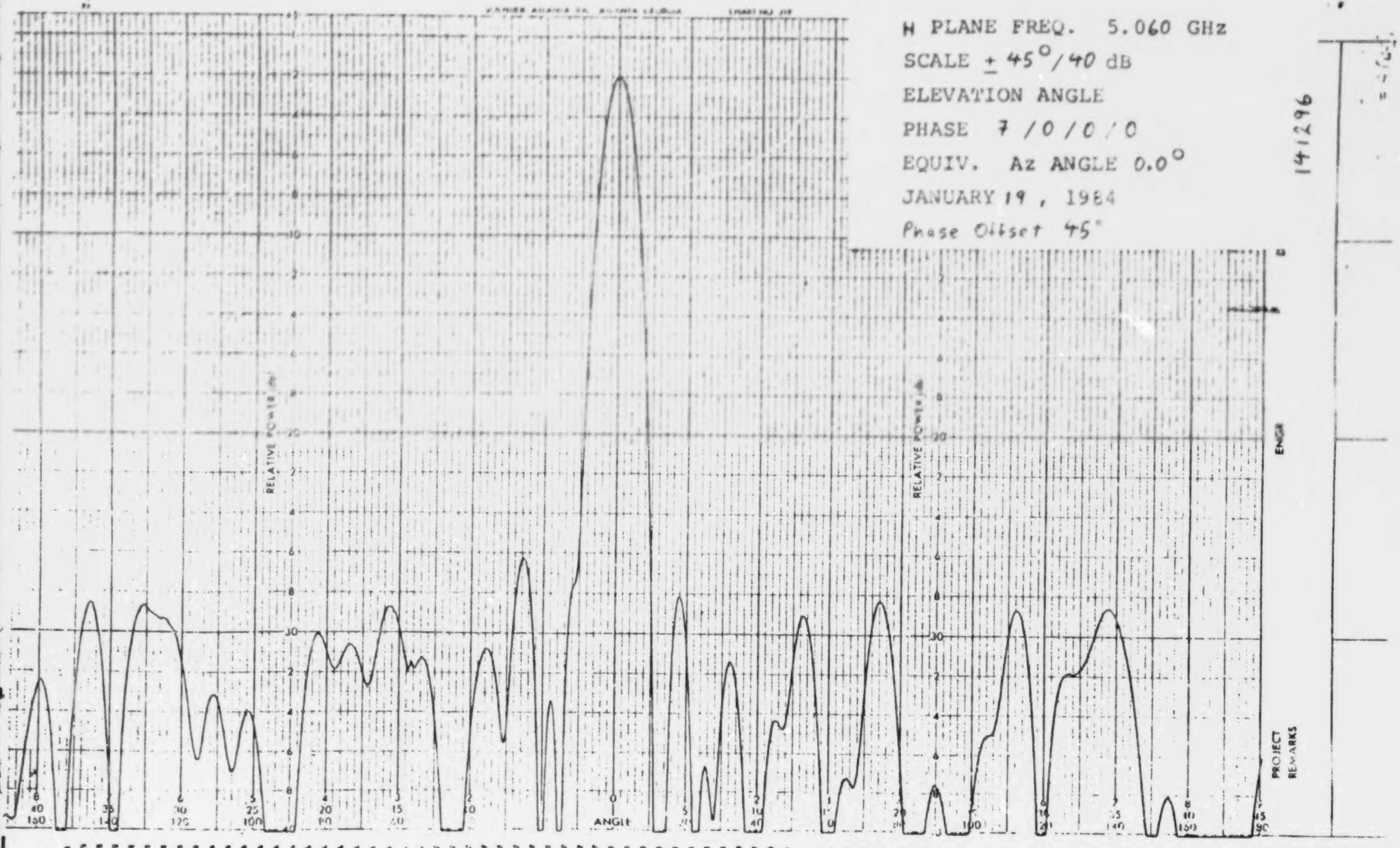
140879


H PLANE FREQ. 5.060 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 7/0/0/0
EQUIV. Az ANGLE 0.0°
JANUARY 19, 1984
Phase Offset 0°
141291
RELATIVE POWER (dB)
ANGLE
PROJECT
REMARKS



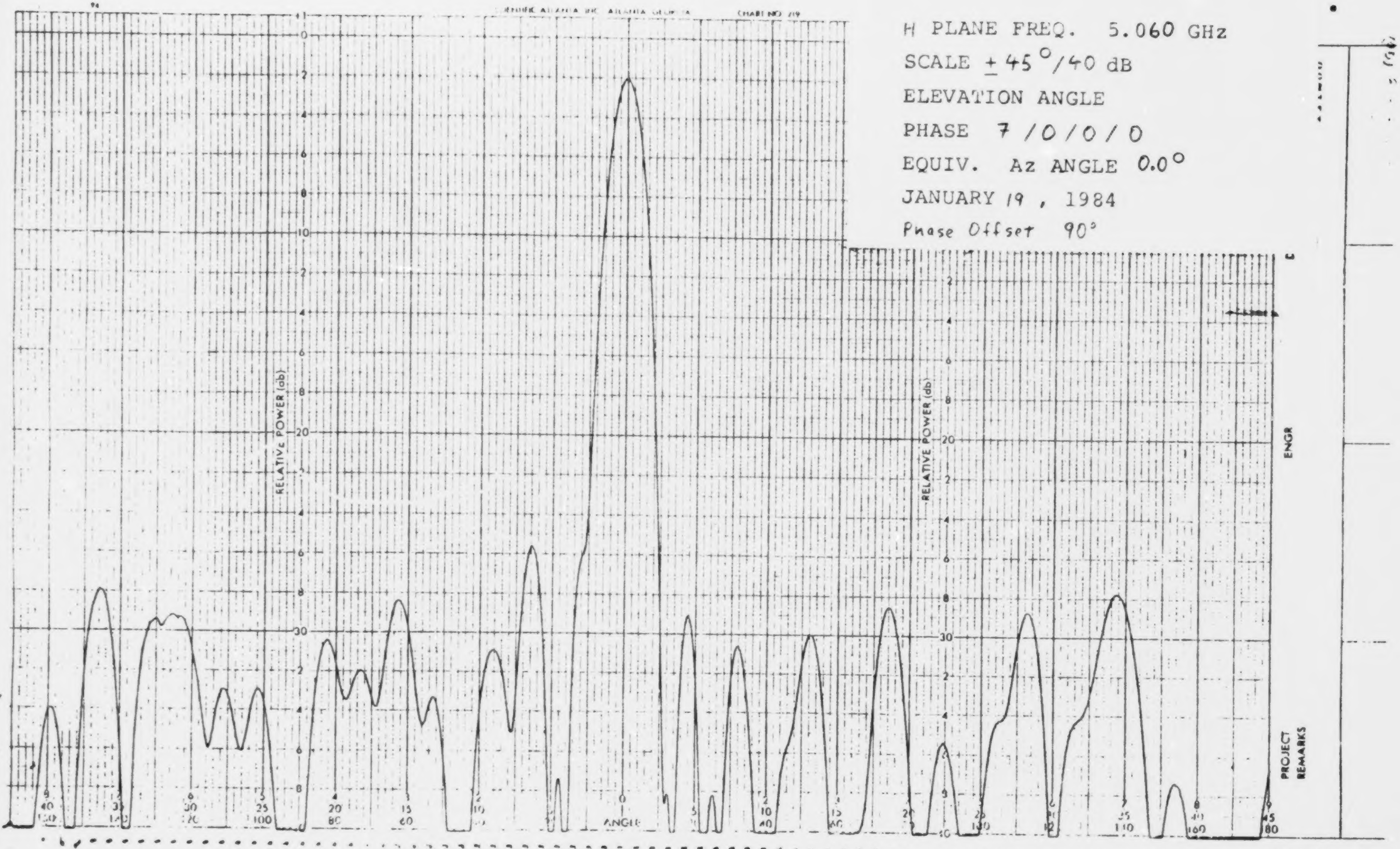
PLANE FREQ. 5.060 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 7/0/0/0
EQUIV. Az ANGLE 0.0°
JANUARY 19, 1984
Phase Offset 22.5°

141293

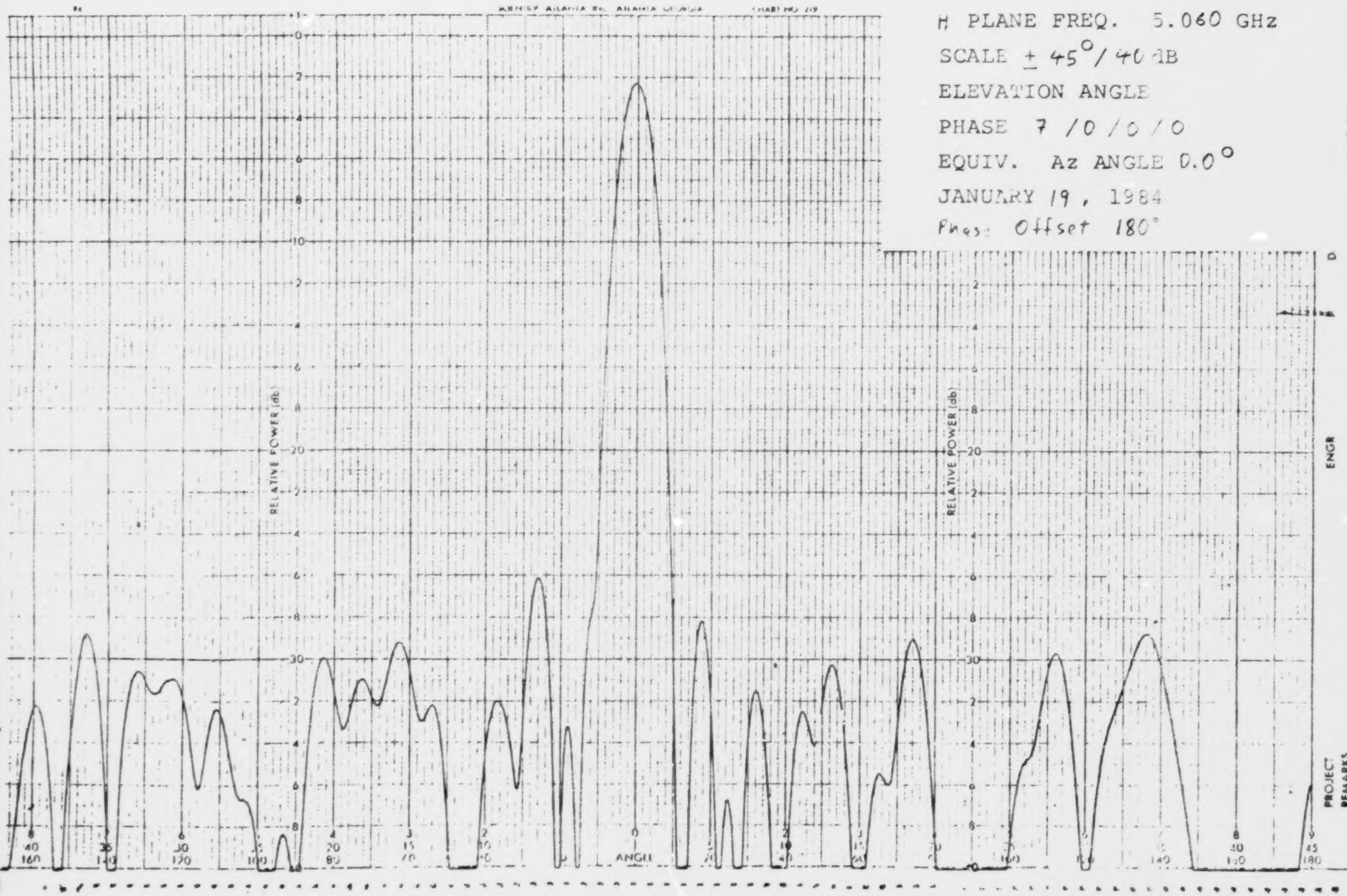


H PLANE FREQ. 5.060 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 7/0/0/0
EQUIV. Az ANGLE 0.0°
JANUARY 19, 1984
Phase Offset 45°

141296

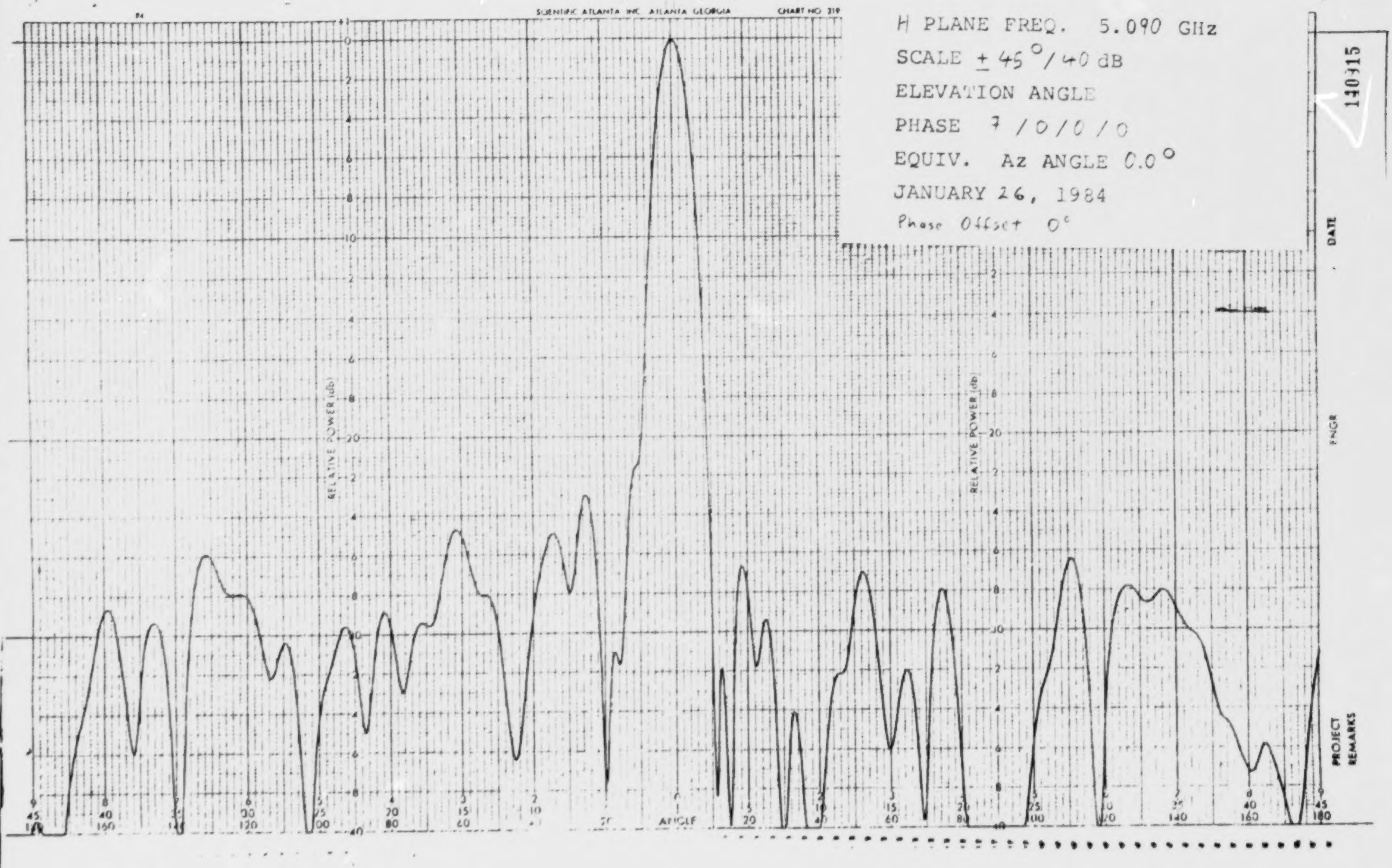


H PLANE FREQ. 5.060 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 7 /0/0/0
EQUIV. Az ANGLE 0.0°
JANUARY 19 , 1984
Phase Offset 90°



H PLANE FREQ. 5.060 GHz
SCALE ± 45°/ 40 dB
ELEVATION ANGLE
PHASE 7 /0 /0 /0
EQUIV. Az ANGLE 0.0°
JANUARY 19 , 1984
Phase Offset 180°

141294



H PLANE FREQ. 5.090 GHz

SCALE ± 45°/40 dB

ELEVATION ANGLE

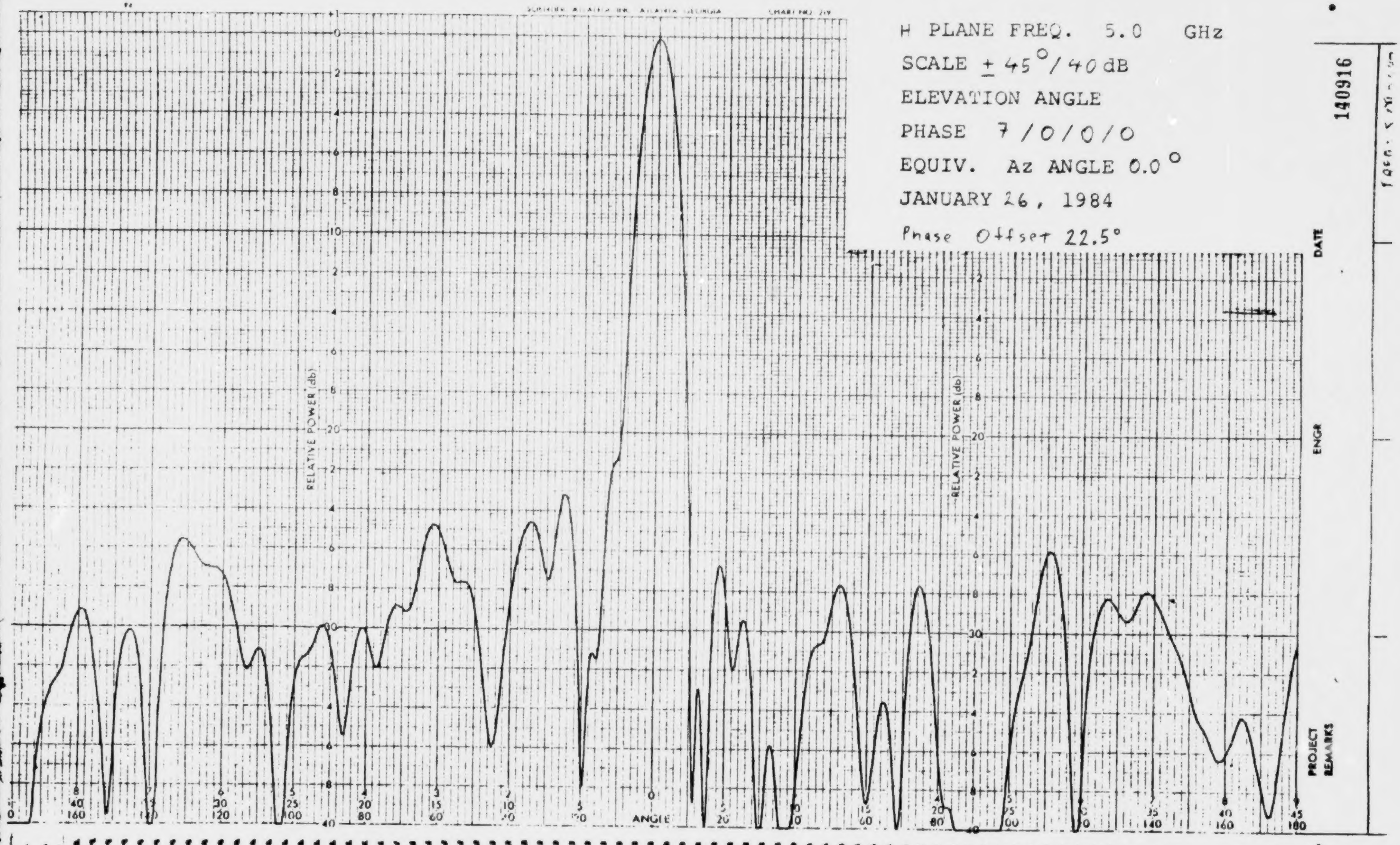
PHASE 7/0/0/0

EQUIV. Az ANGLE 0.0°

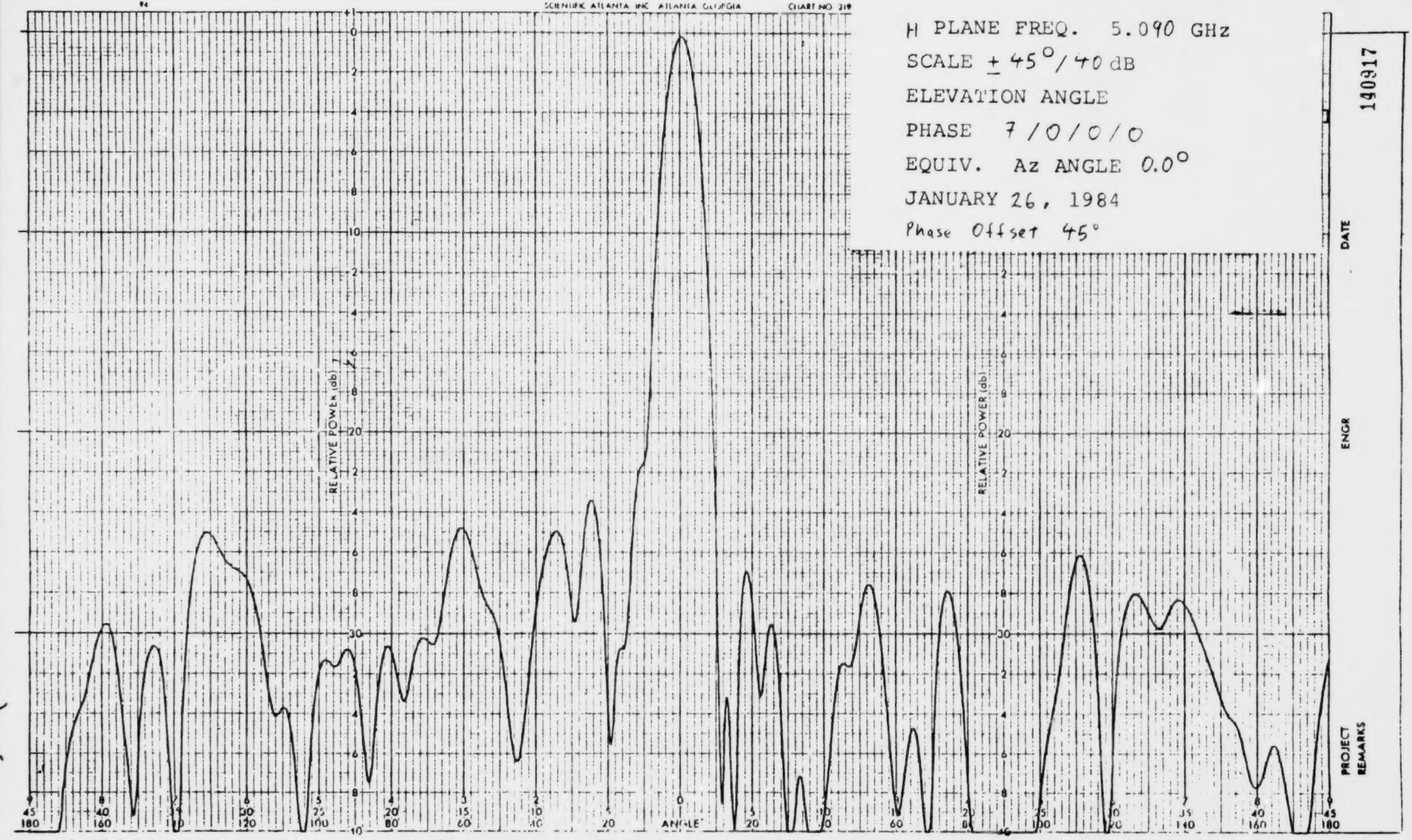
JANUARY 26, 1984

Phase Offset 0°

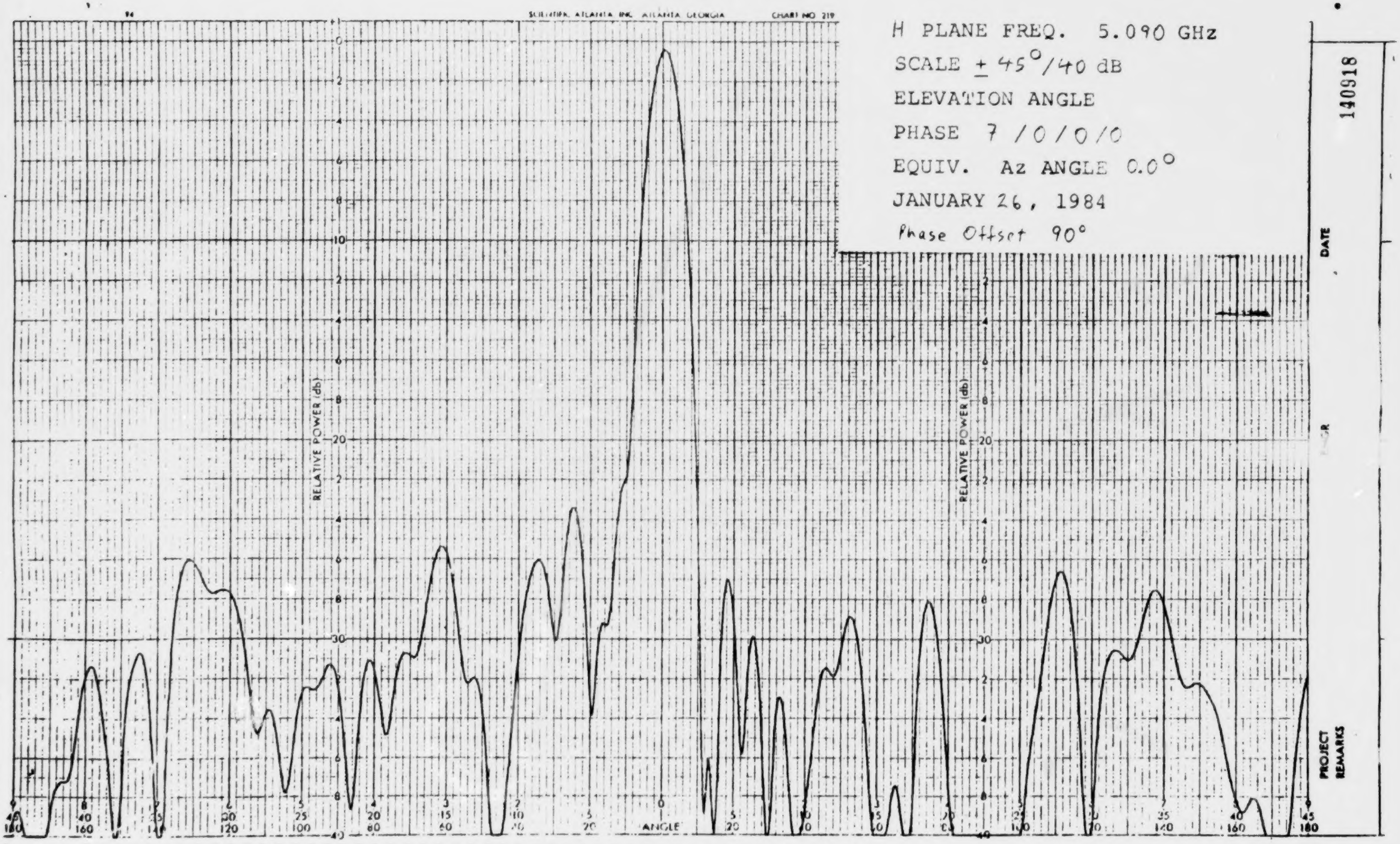
140315



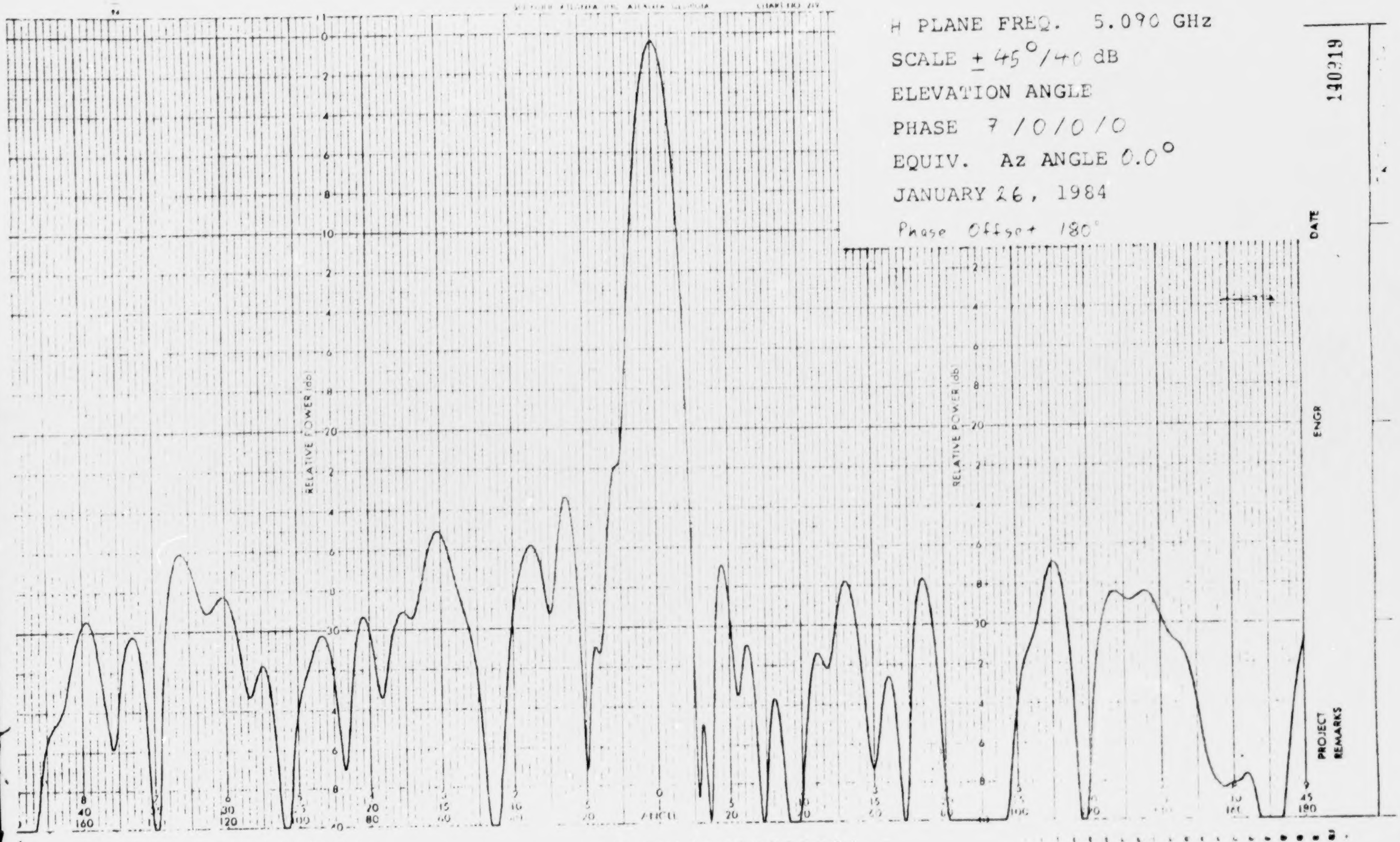
H PLANE FREQ. 5.0 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 7/0/0/0
EQUIV. Az ANGLE 0.0°
JANUARY 26, 1984
Phase Offset 22.5°



H PLANE FREQ. 5.090 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 7/0/0/0
EQUIV. Az ANGLE 0.0°
JANUARY 26, 1984
Phase Offset 45°



H PLANE FREQ. 5.090 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 7 /0/0/0
EQUIV. Az ANGLE 0.0°
JANUARY 26, 1984
Phase Offset 90°



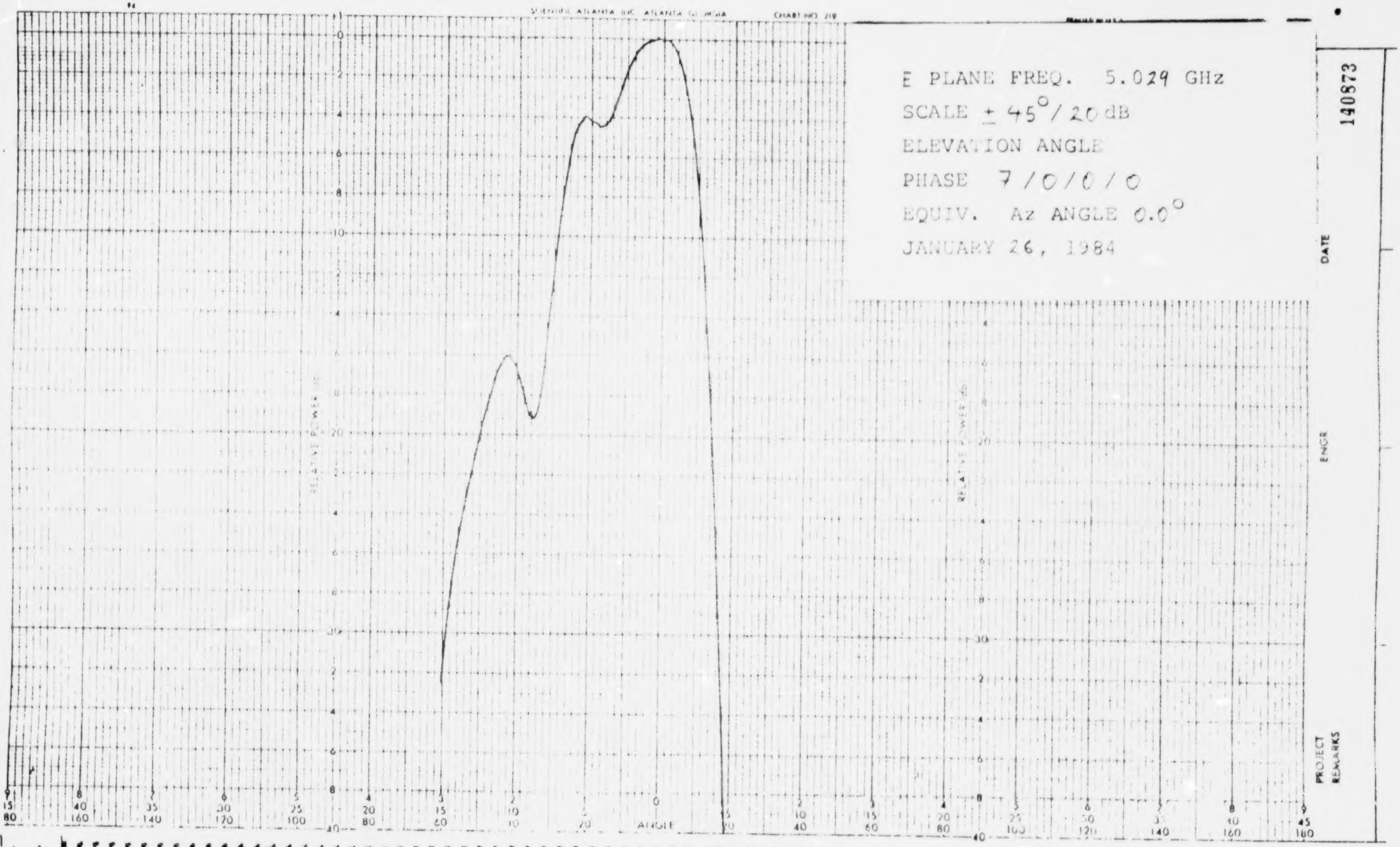
H PLANE FREQ. 5.090 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE
PHASE 7/0/0/0
EQUIV. Az ANGLE 0.0°
JANUARY 26, 1984
Phase Offset 180°

APPENDIX 4

Elevation Scans

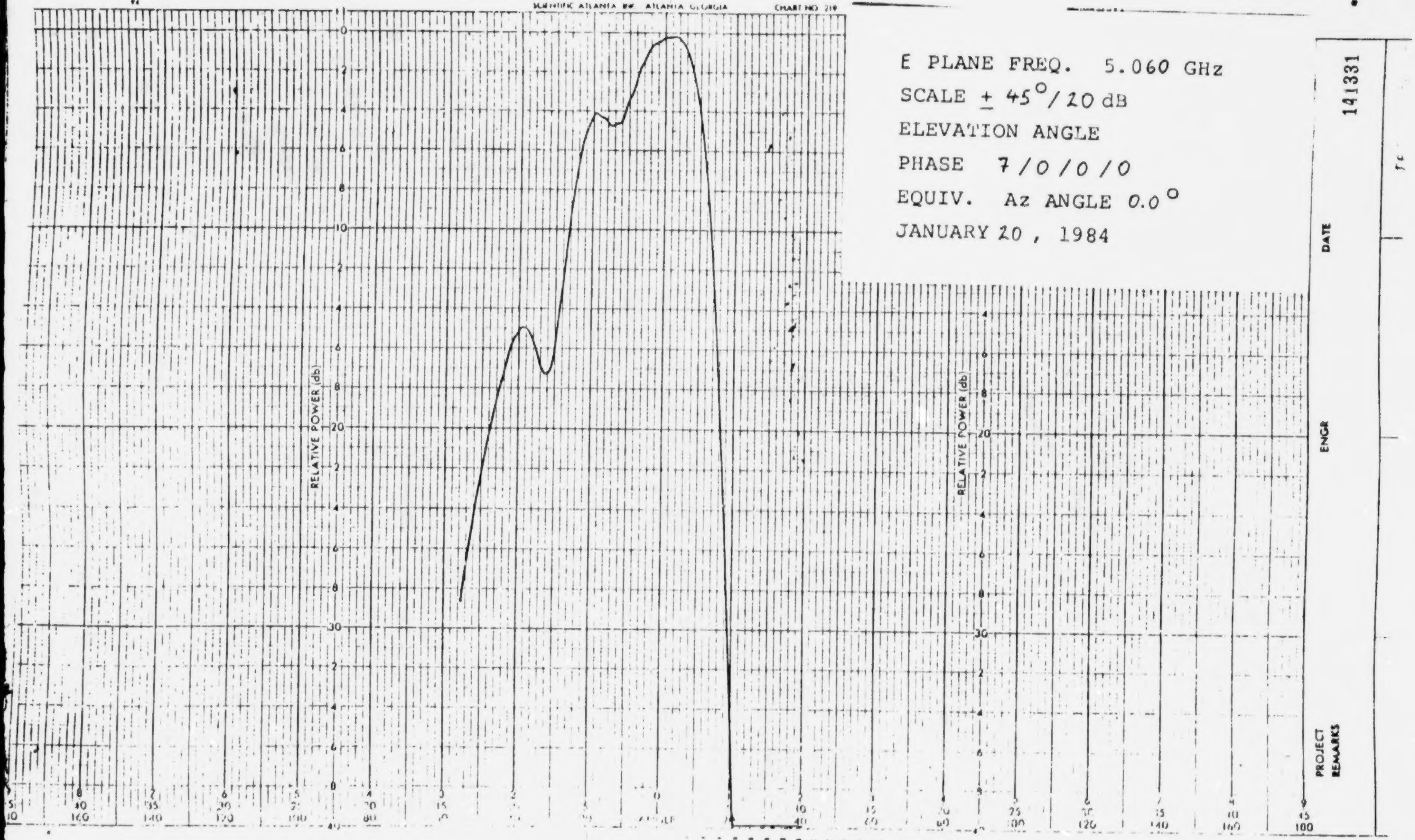
for

5030, 5060, 5090 MHz for azimuth angle 0°

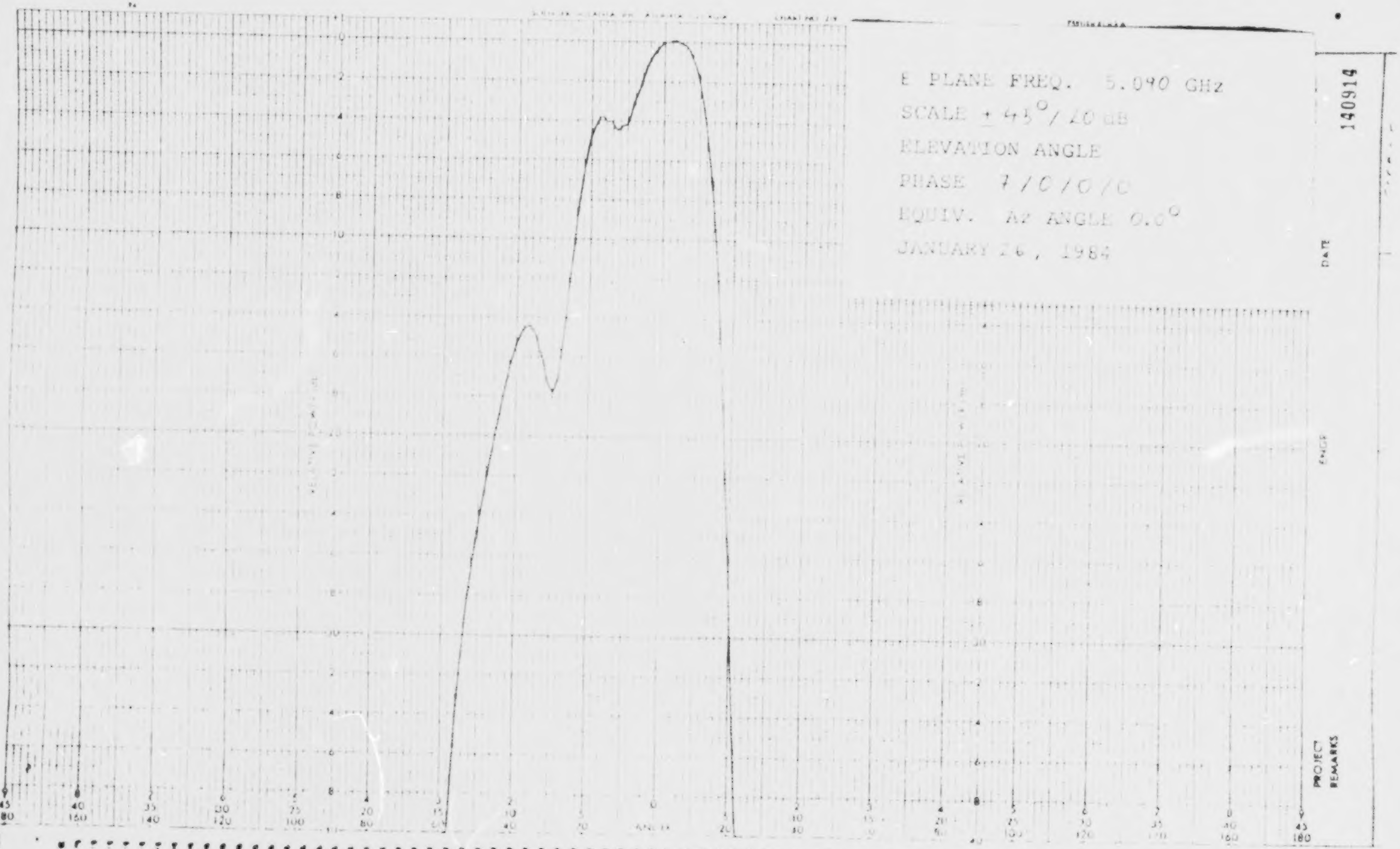


E PLANE FREQ. 5.029 GHz
SCALE ± 45°/20 dB
ELEVATION ANGLE
PHASE 7/0/0/0
EQUIV. Az ANGLE 0.0°
JANUARY 26, 1984

140873



E PLANE FREQ. 5.060 GHz
SCALE ± 45°/20 dB
ELEVATION ANGLE
PHASE 7/0/0/0
EQUIV. Az ANGLE 0.0°
JANUARY 20, 1984



140914

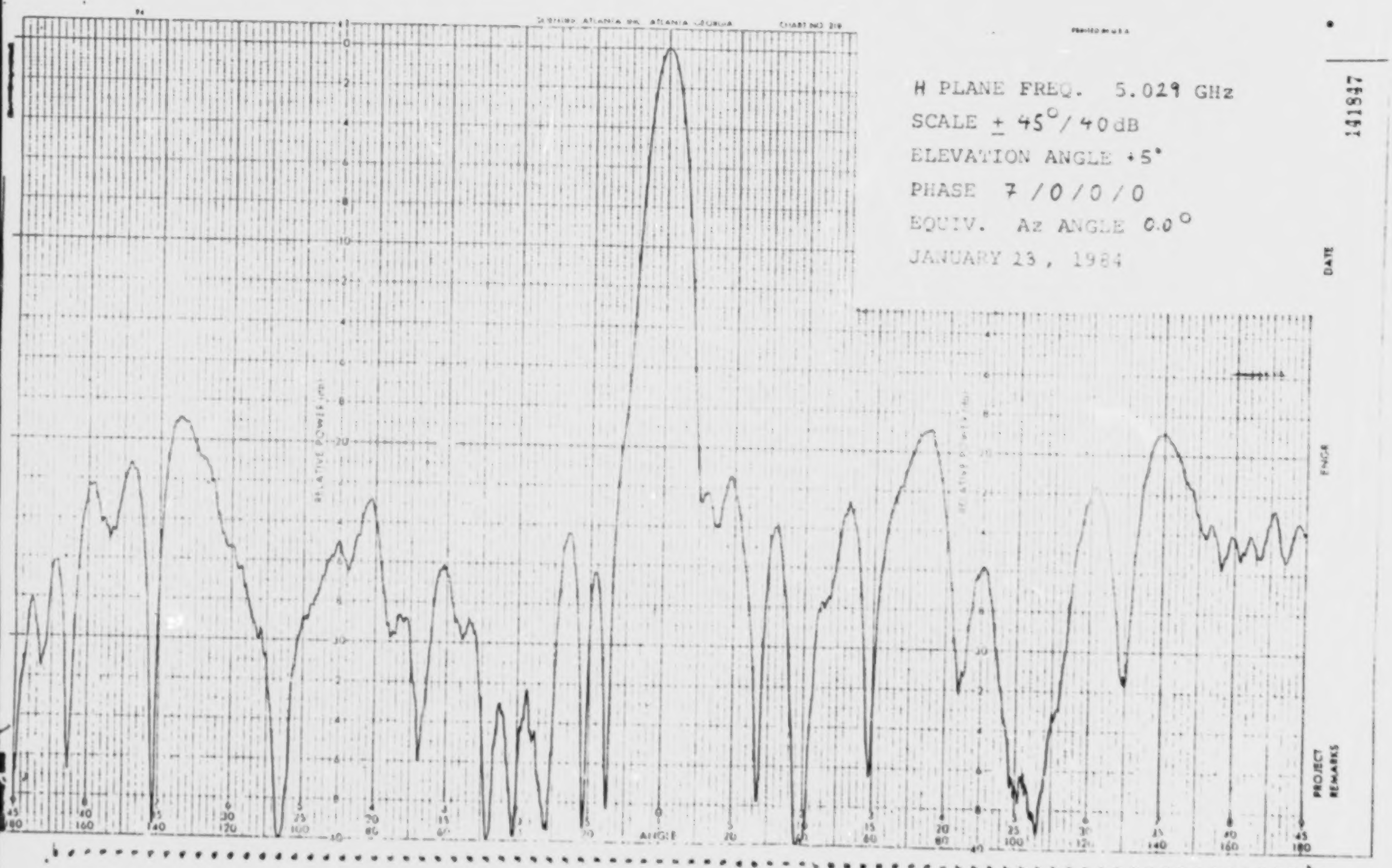
E PLANE FREQ. 5.090 GHz
SCALE ± 45°/ 20 dB
ELEVATION ANGLE
PHASE 7/0/0/0
EQUIV. AZ ANGLE 0.0°
JANUARY 26, 1984

APPENDIX 5

Azimuth Scans

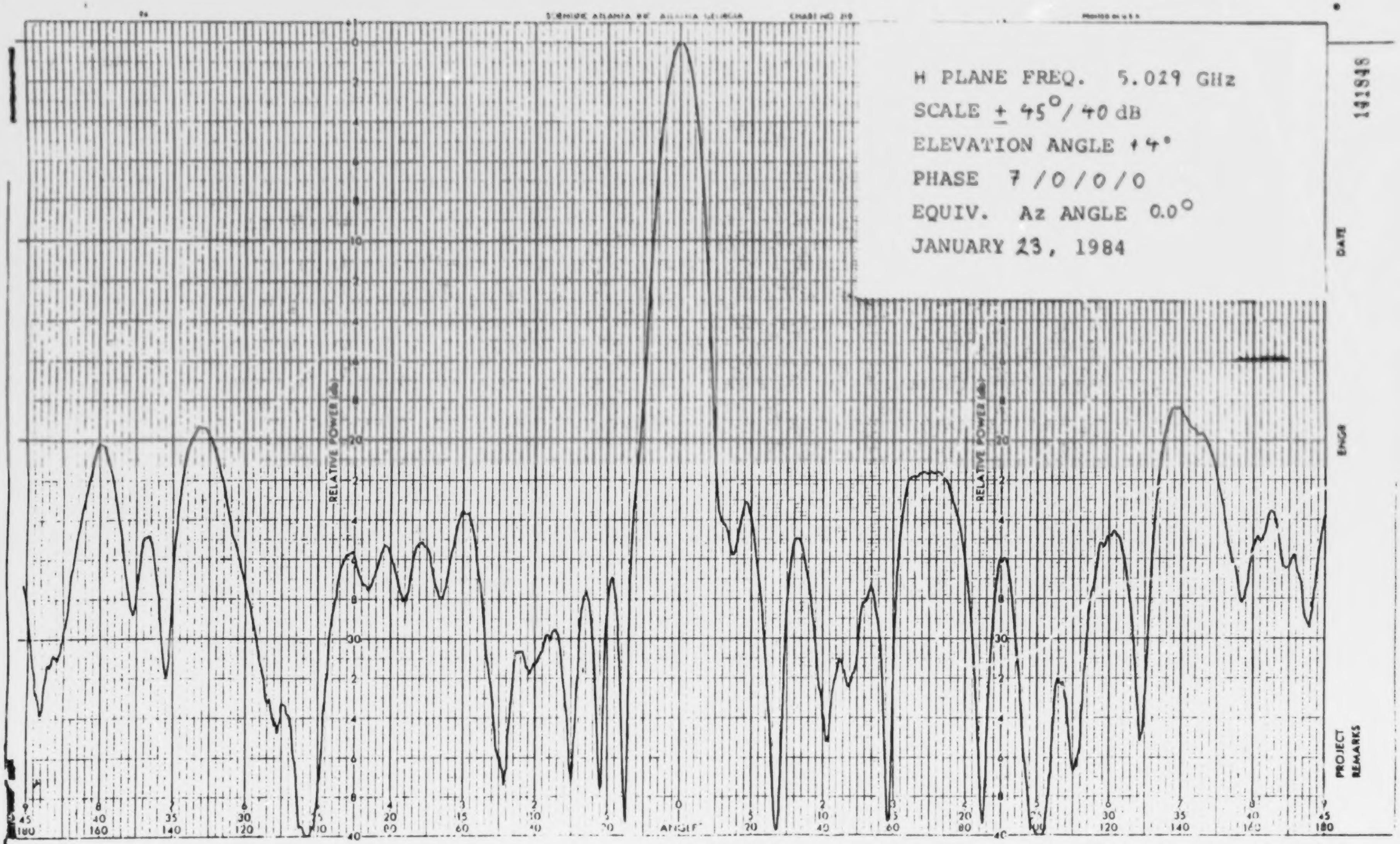
for

every 1° of elevation angle with azimuth angle 0 degrees

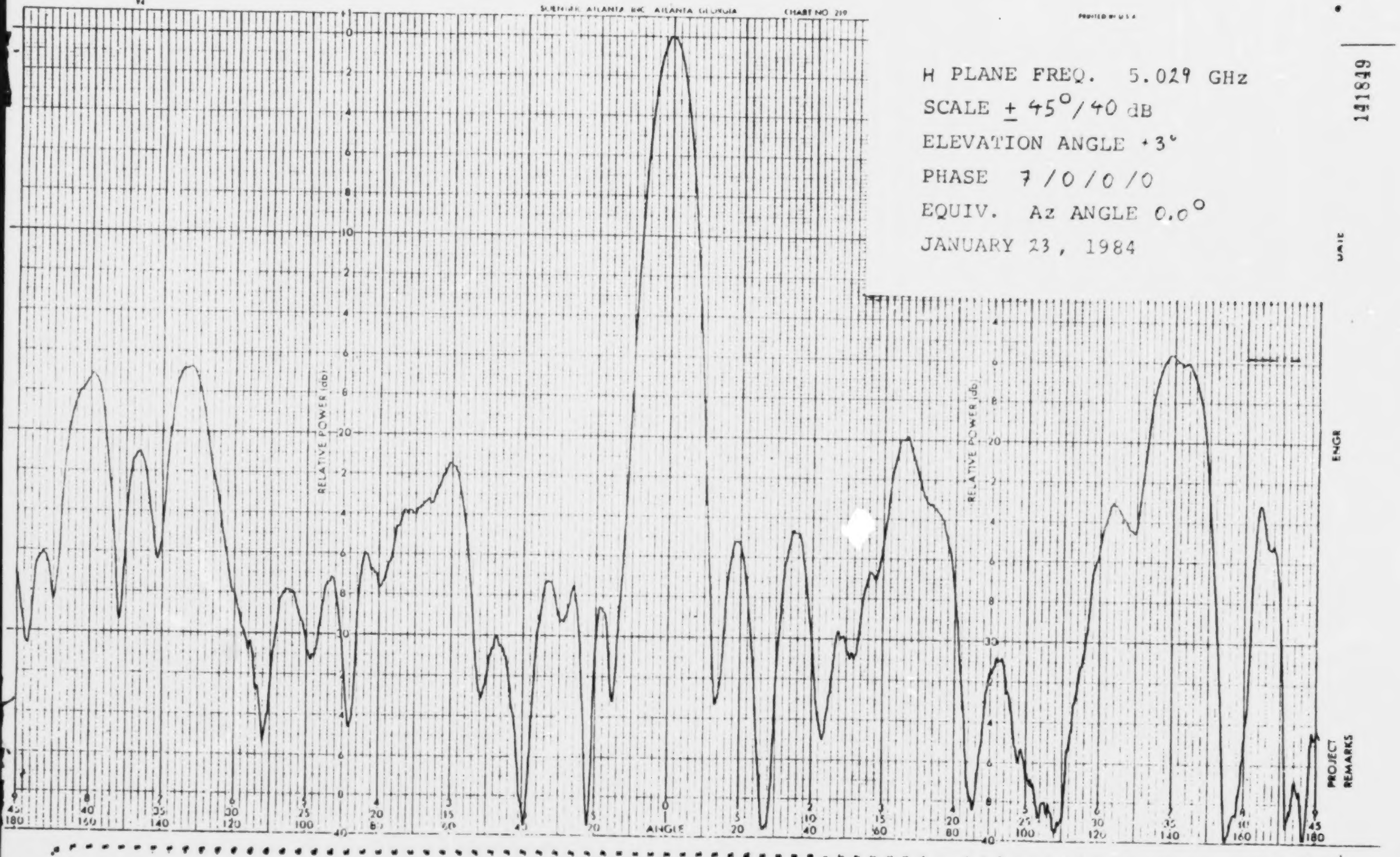


H PLANE FREQ. 5.029 GHz
SCALE ± 45°/40dB
ELEVATION ANGLE +5°
PHASE 7/0/0/0
EQUIV. Az ANGLE 0.0°
JANUARY 23, 1984

141847



H PLANE FREQ. 5.029 GHz
SCALE ± 45°/ 40 dB
ELEVATION ANGLE +4°
PHASE 7 /0/0/0
EQUIV. Az ANGLE 0.0°
JANUARY 23, 1984



H PLANE FREQ. 5.029 GHz

SCALE ± 45°/40 dB

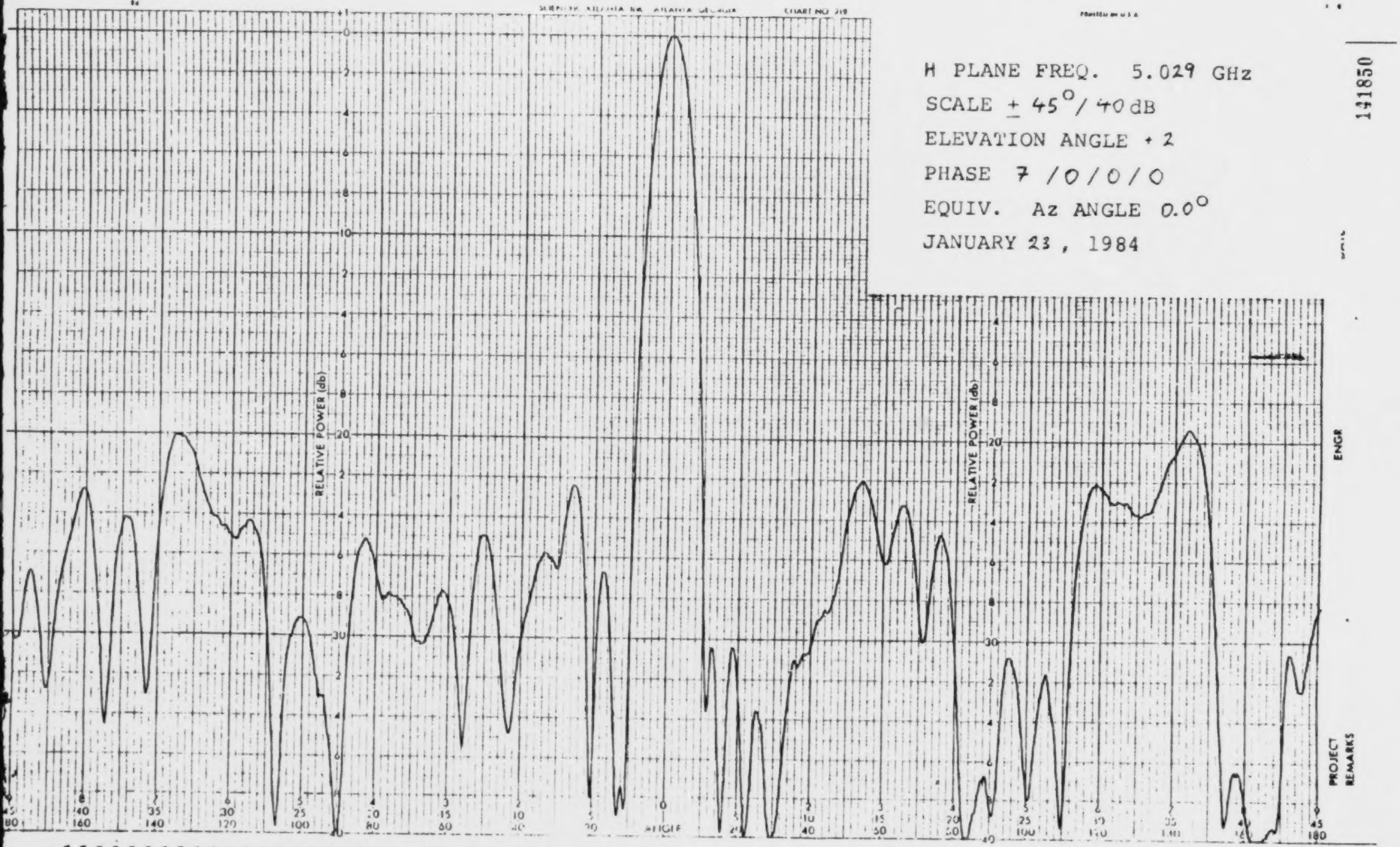
ELEVATION ANGLE +3°

PHASE 7/0/0/0

EQUIV. Az ANGLE 0.0°

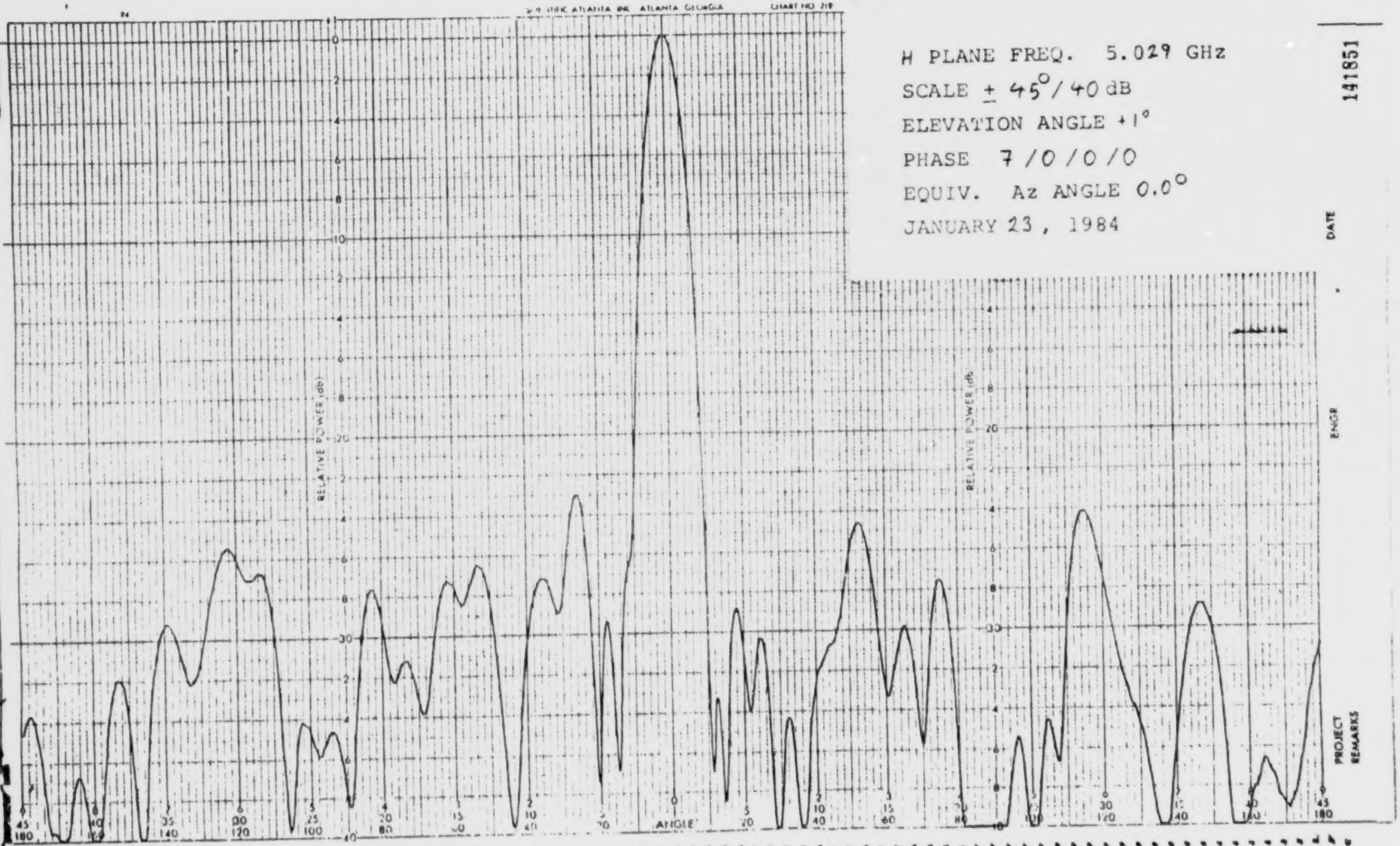
JANUARY 23, 1984

141849



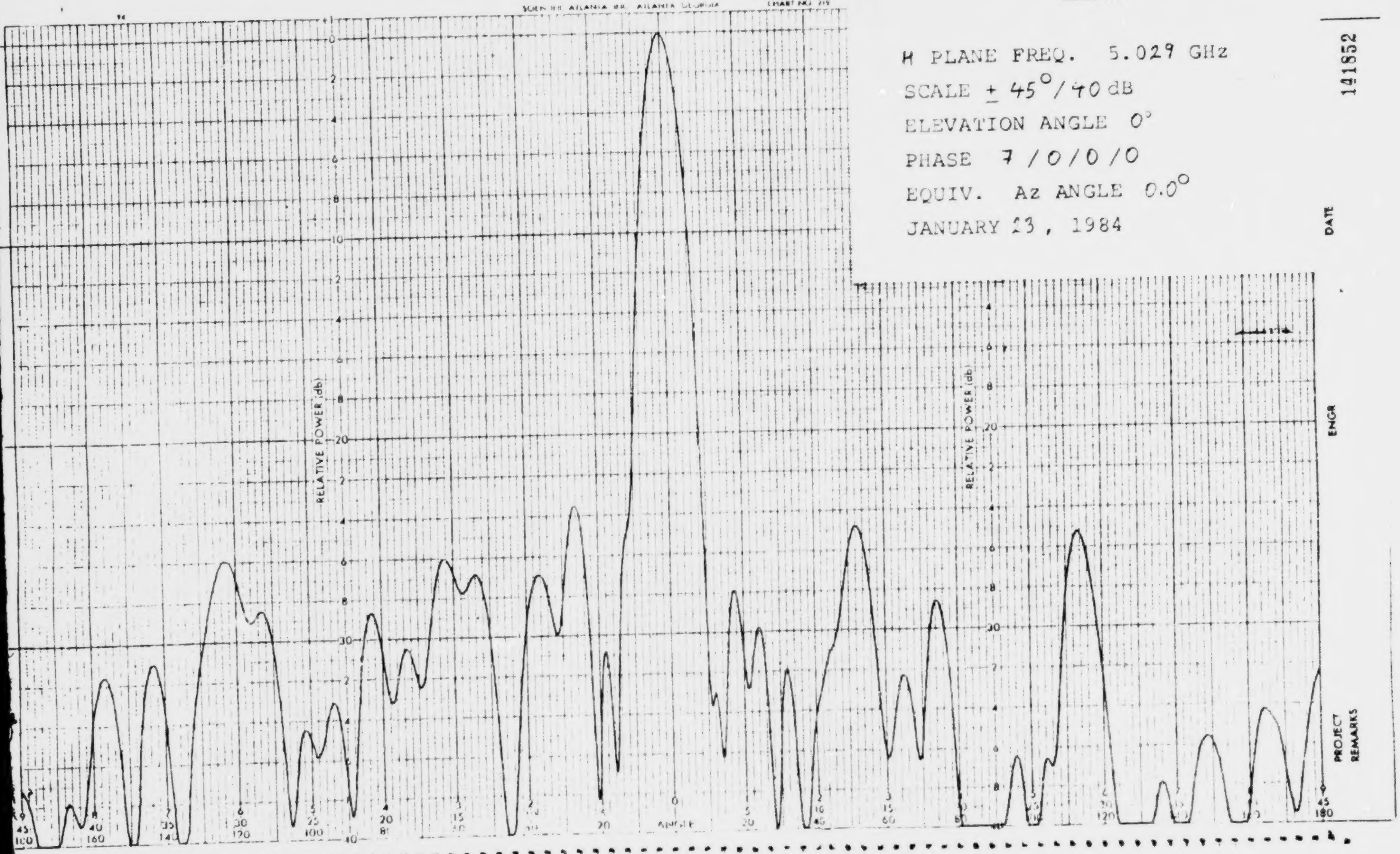
H PLANE FREQ. 5.029 GHz
SCALE ± 45°/ 40 dB
ELEVATION ANGLE + 2
PHASE 7 /0/0/0
EQUIV. Az ANGLE 0.0°
JANUARY 23 , 1984

141850



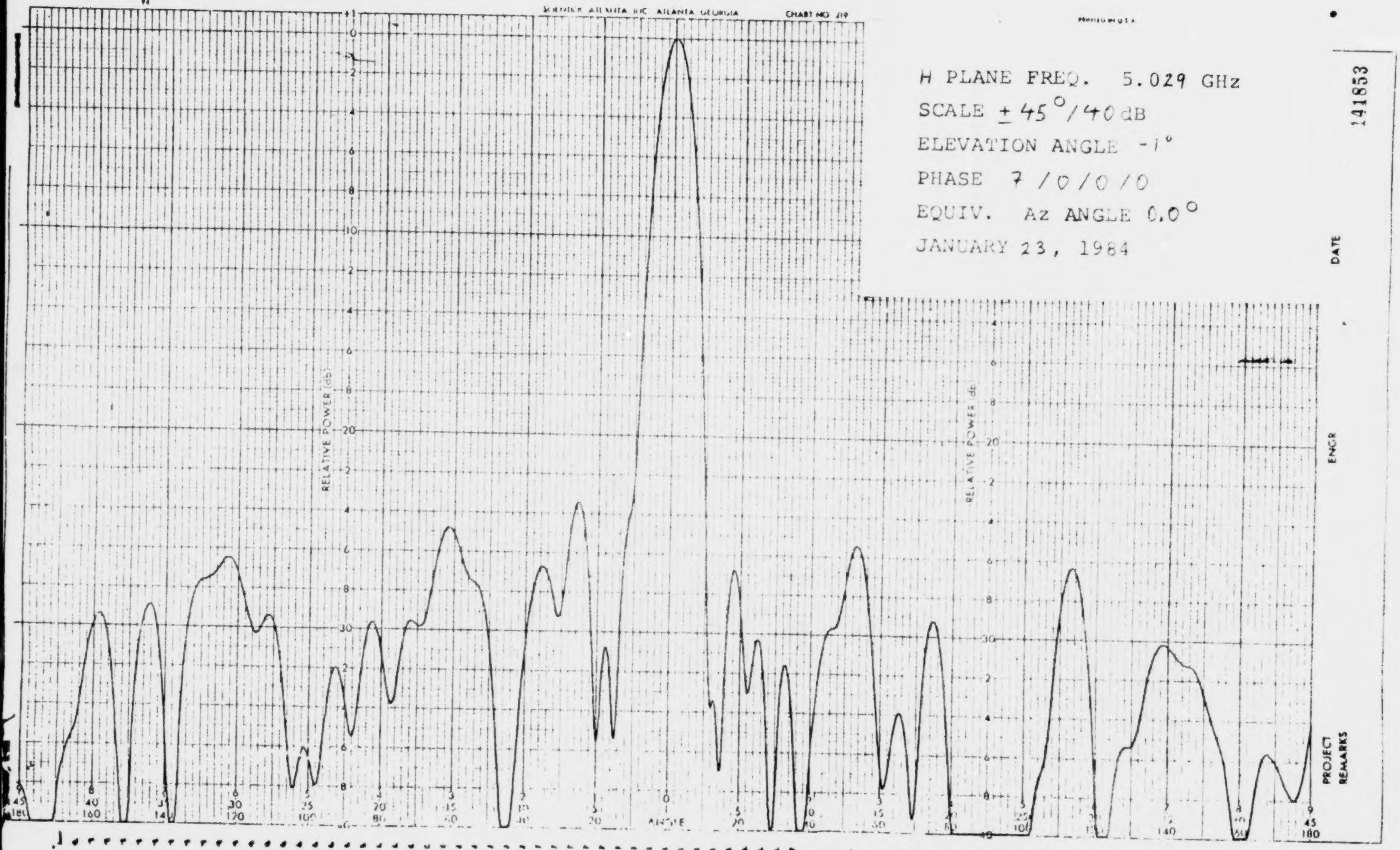
H PLANE FREQ. 5.029 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE +1°
PHASE 7/0/0/0
EQUIV. Az ANGLE 0.0°
JANUARY 23, 1984

141851

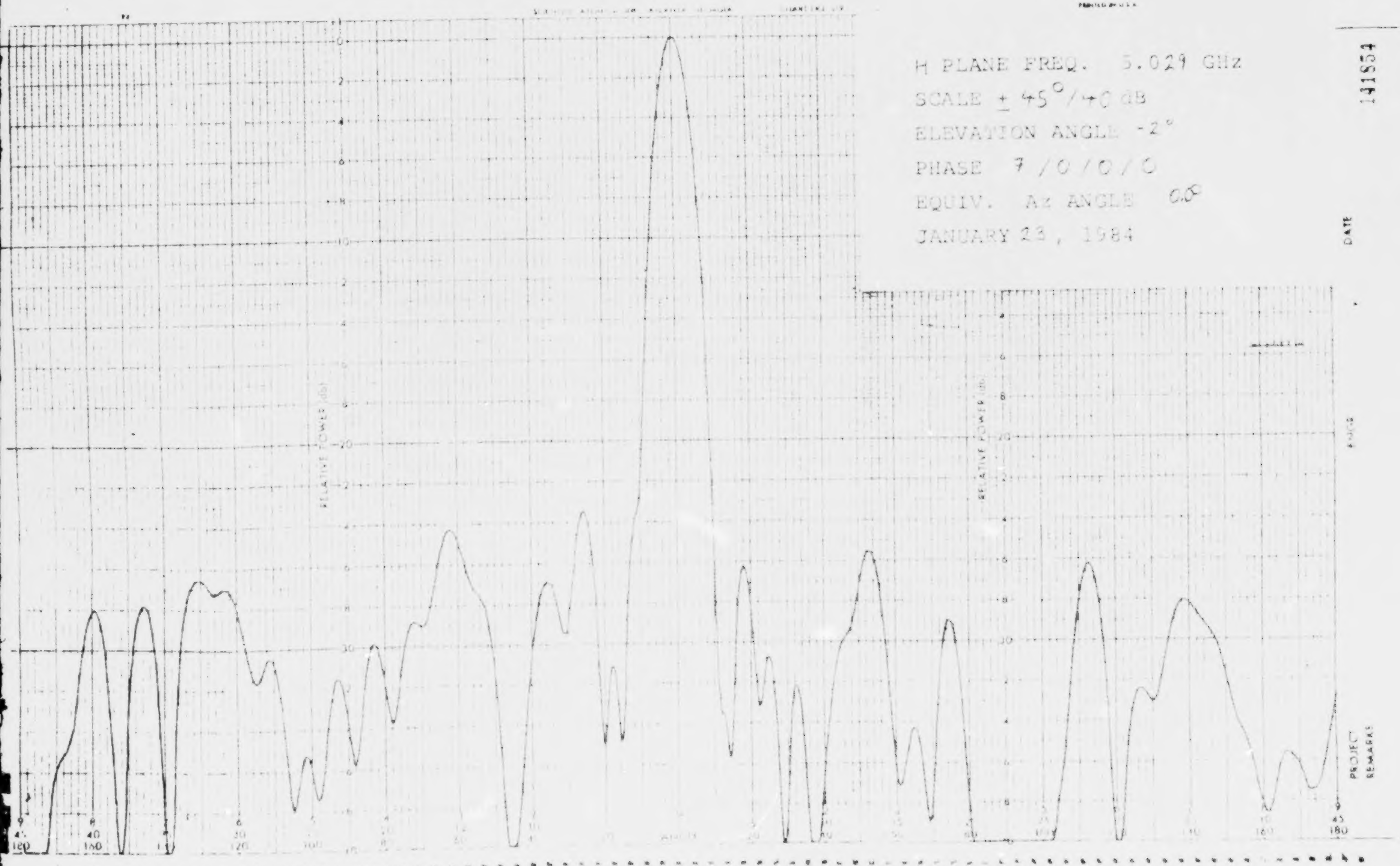


H PLANE FREQ. 5.029 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE 0°
PHASE 7/0/0/0
EQUIV. Az ANGLE 0.0°
JANUARY 23, 1984

141852

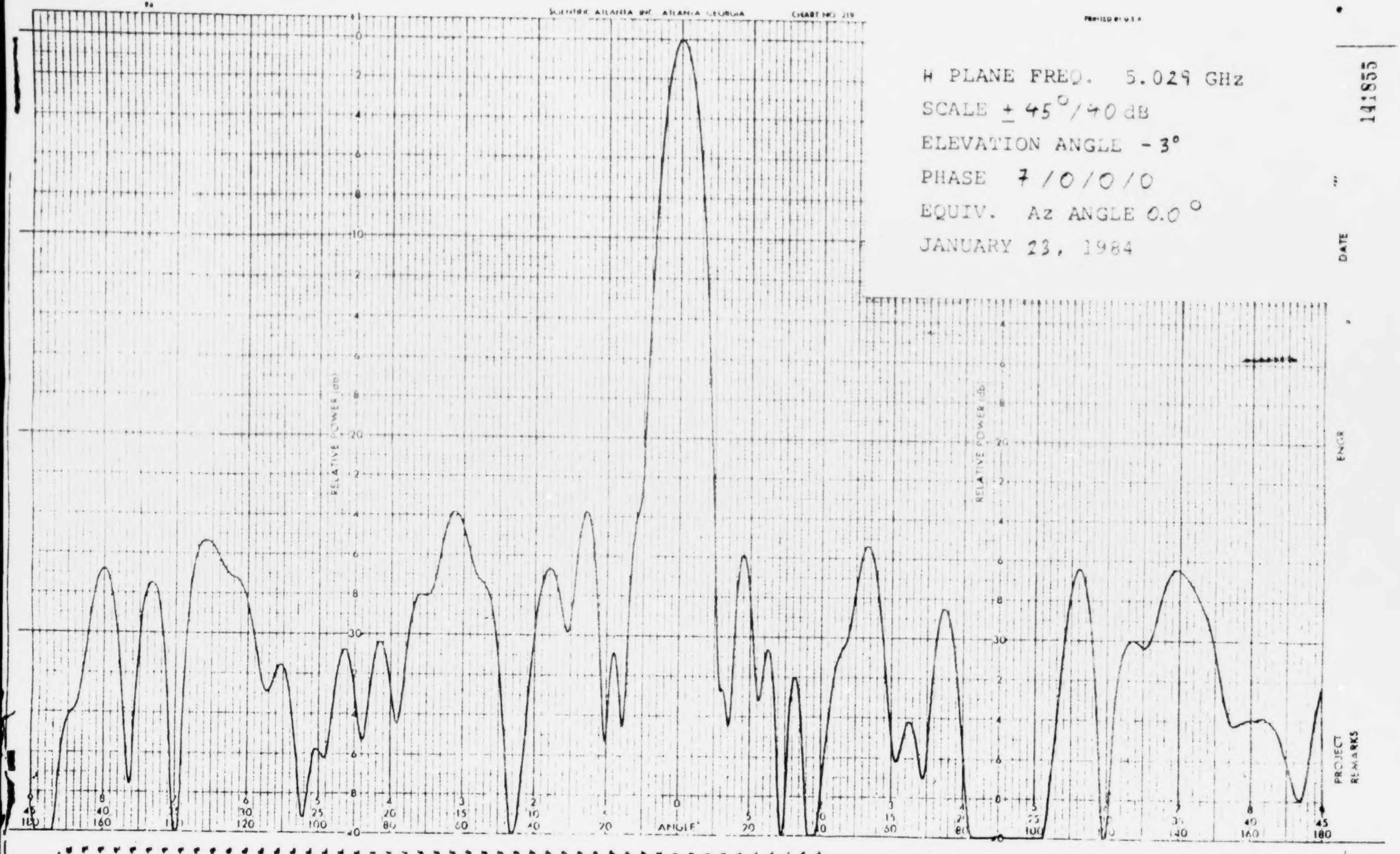


H PLANE FREQ. 5.029 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE -1°
PHASE 7/0/0/0
EQUIV. Az ANGLE 0.0°
JANUARY 23, 1984

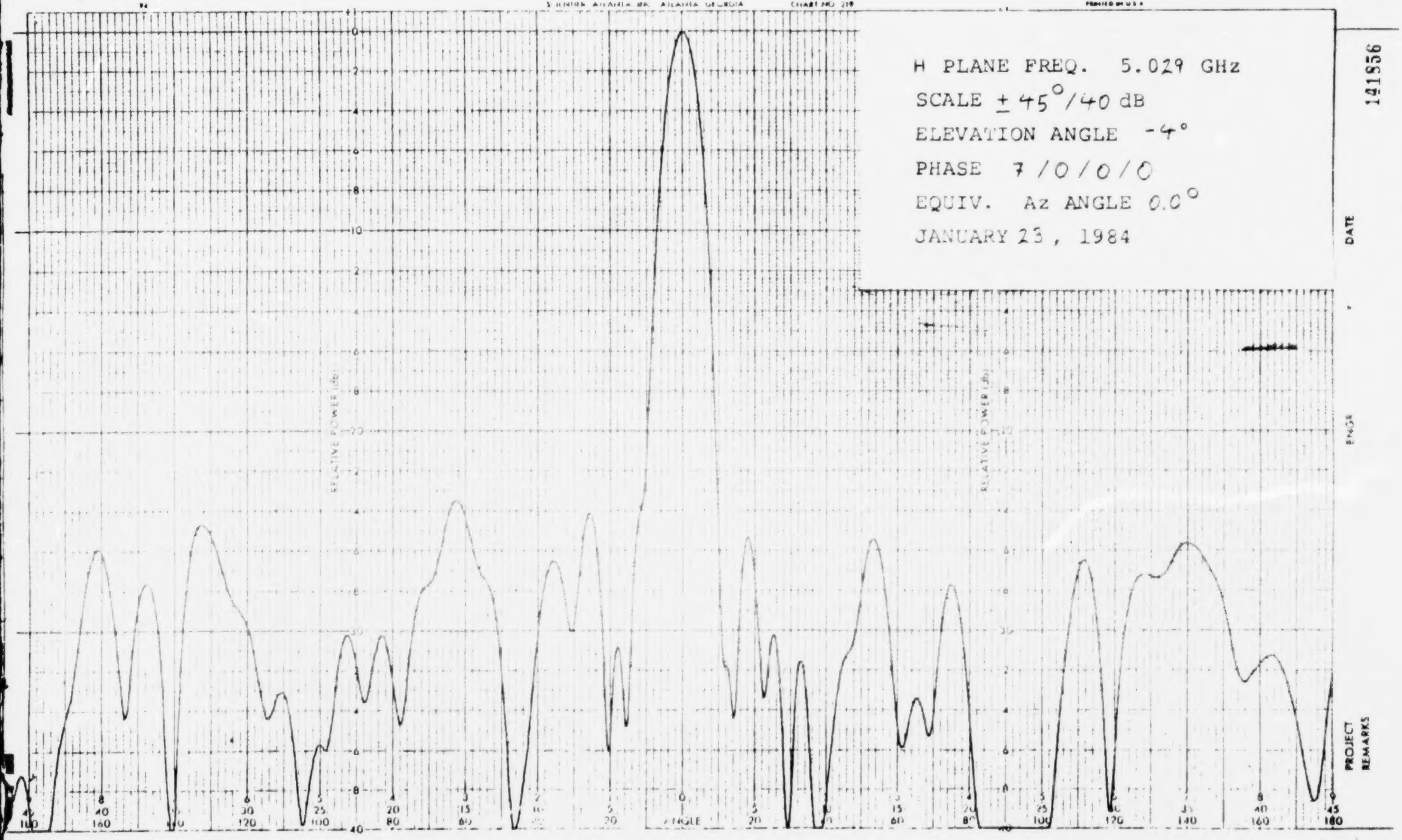


H PLANE FREQ. 5.029 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE -2°
PHASE 7/0/0/0
EQUIV. Az ANGLE 0.0
JANUARY 23, 1984

141854

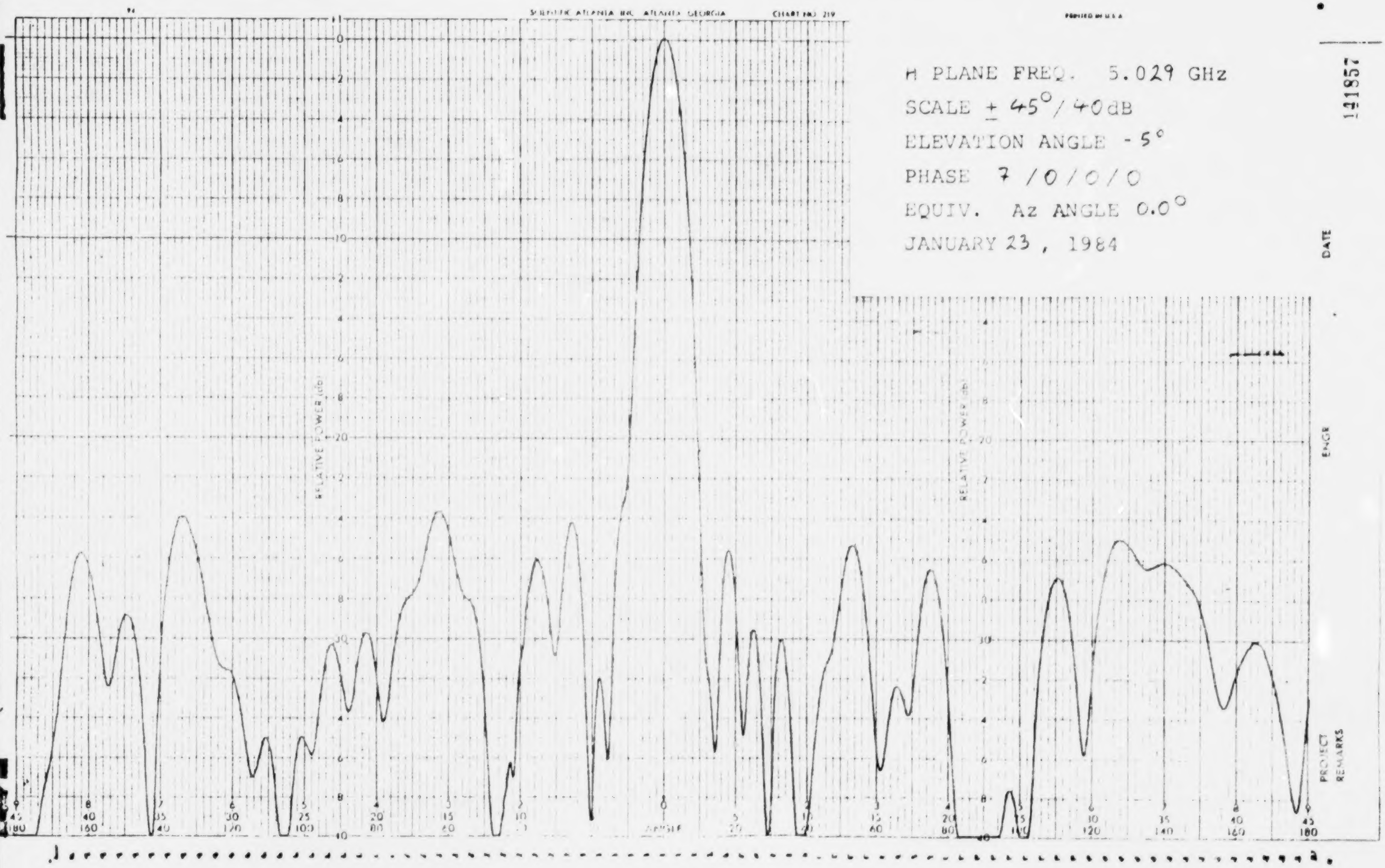


H PLANE FREQ. 5.029 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE - 3°
PHASE 7/0/0/0
EQUIV. Az ANGLE 0.0°
JANUARY 23, 1984



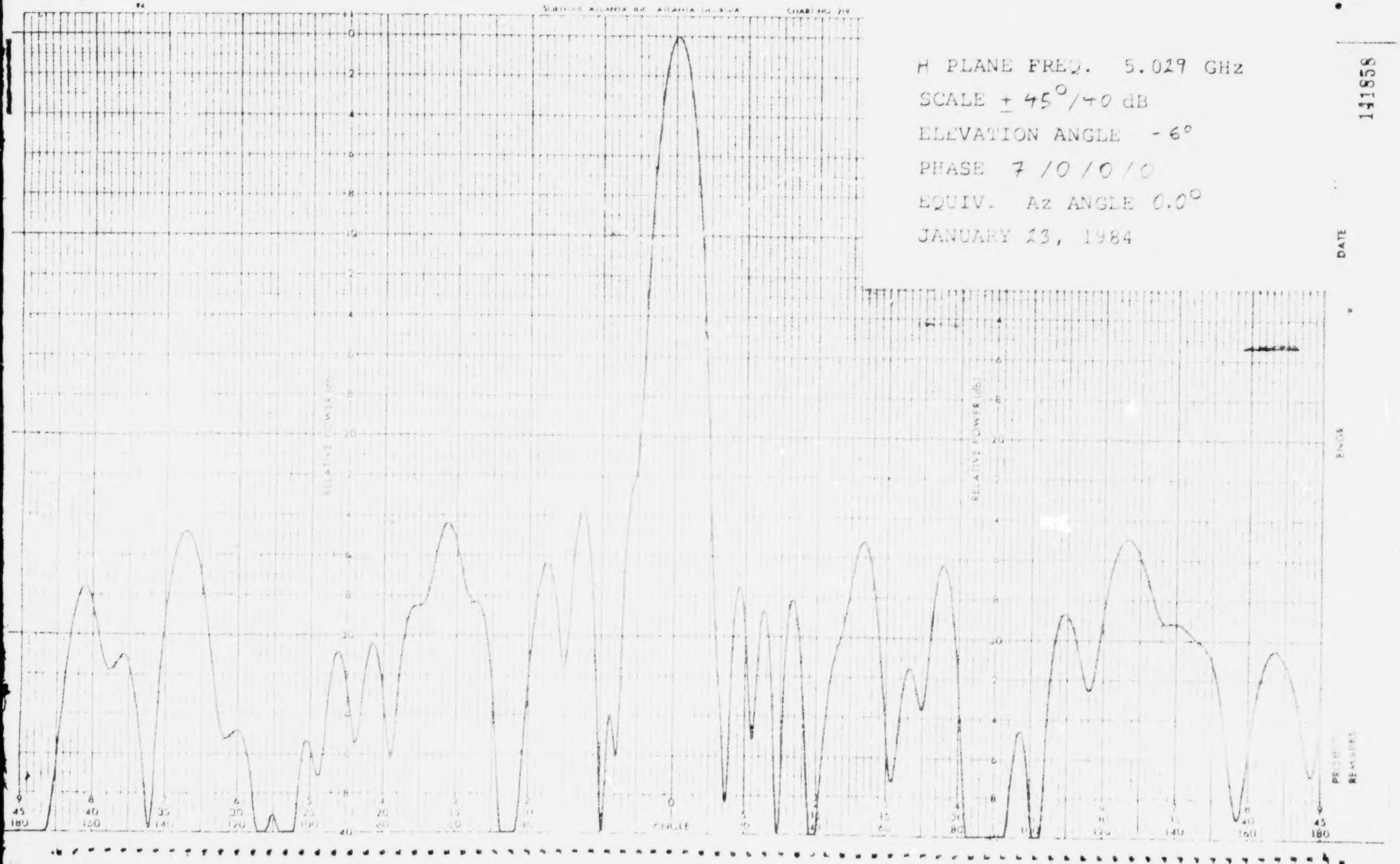
H PLANE FREQ. 5.029 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE -4°
PHASE 7/0/0/0
EQUIV. Az ANGLE 0.0°
JANUARY 23, 1984

141856



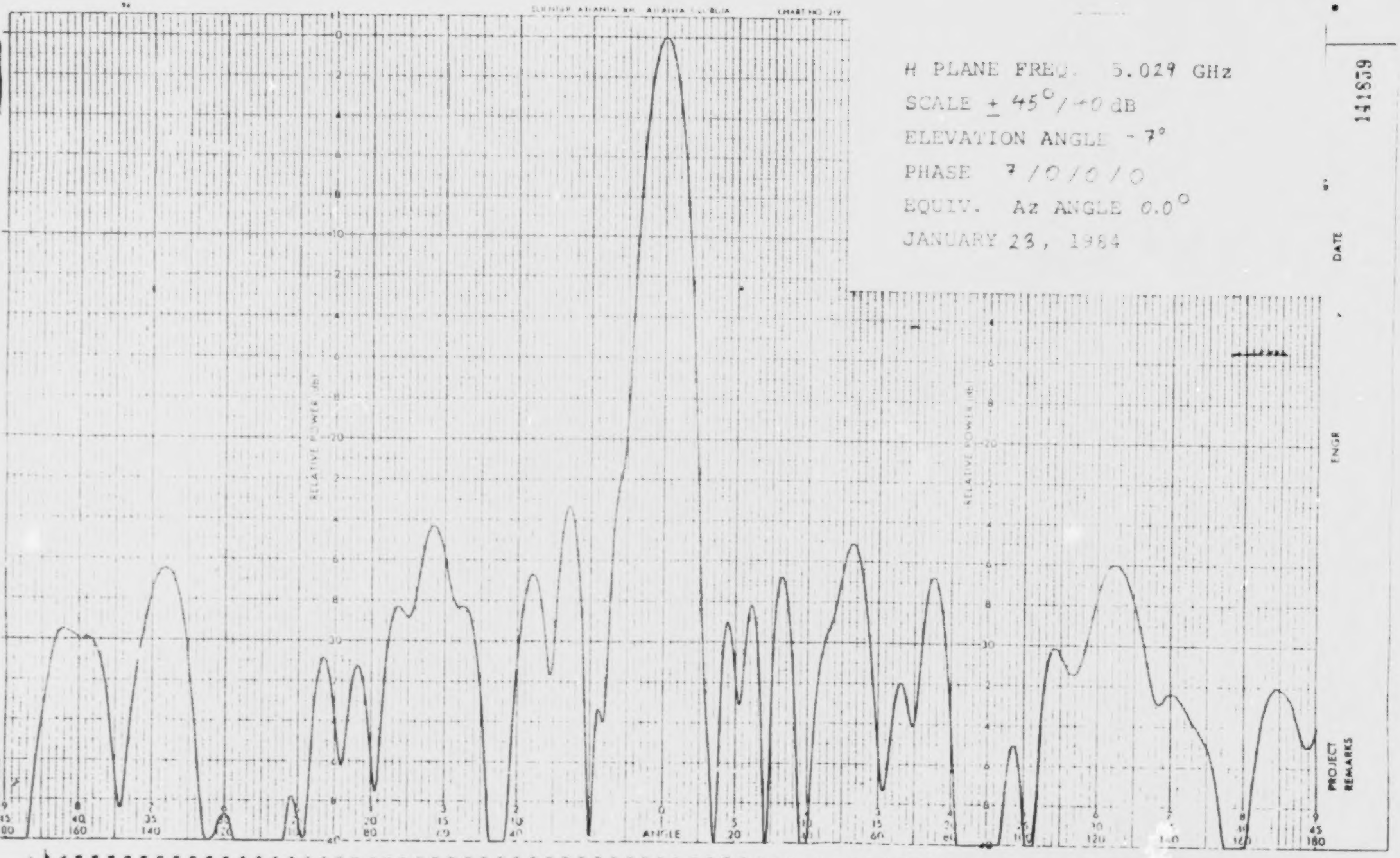
H PLANE FREQ. 5.029 GHz
SCALE ± 45°/40dB
ELEVATION ANGLE -5°
PHASE 7/0/0/0
EQUIV. Az ANGLE 0.0°
JANUARY 23, 1984

141857



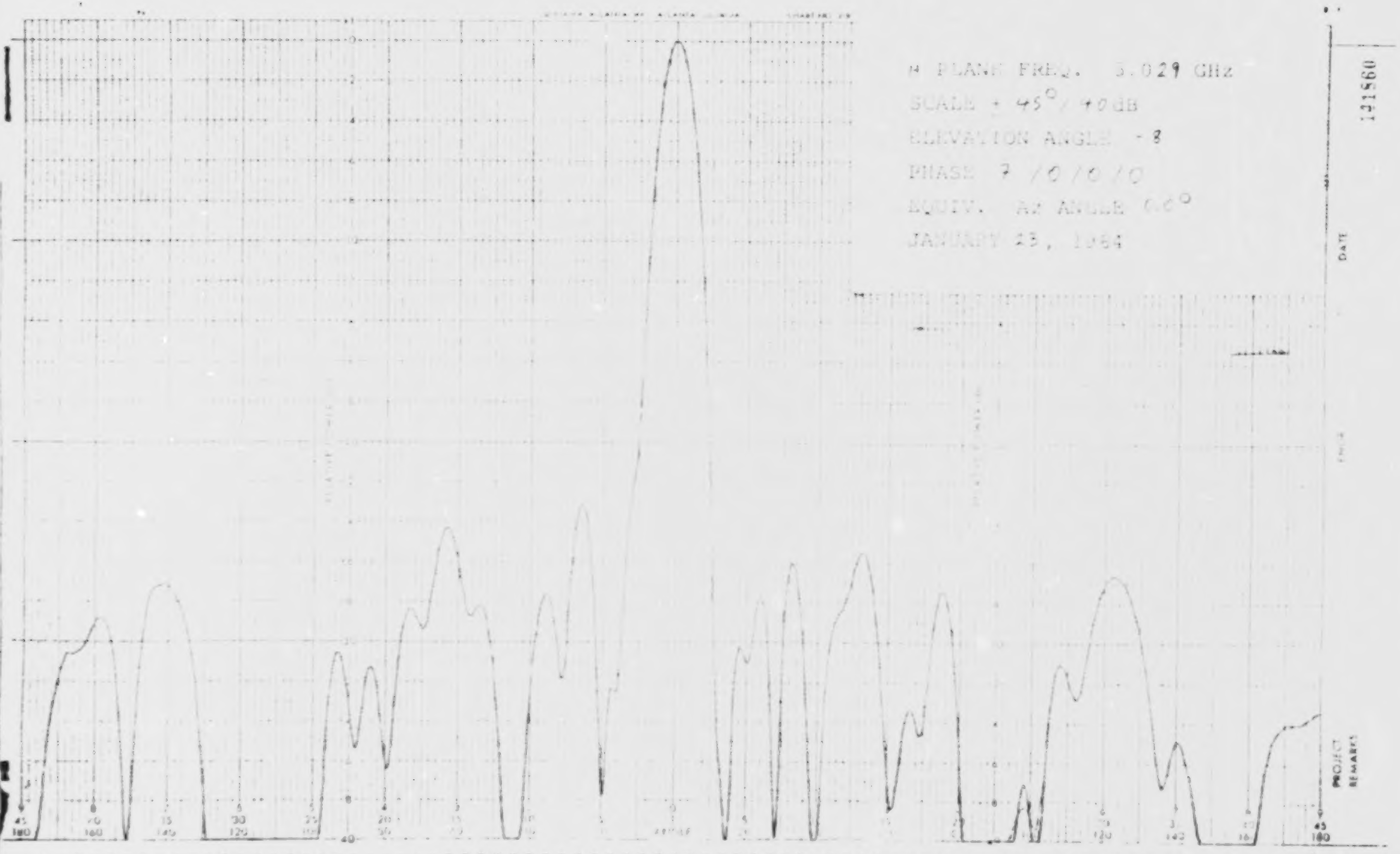
H PLANE FREQ. 5.029 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE -6°
PHASE 7/0/0/0
EQUIV. Az ANGLE 0.0°
JANUARY 23, 1984

141858

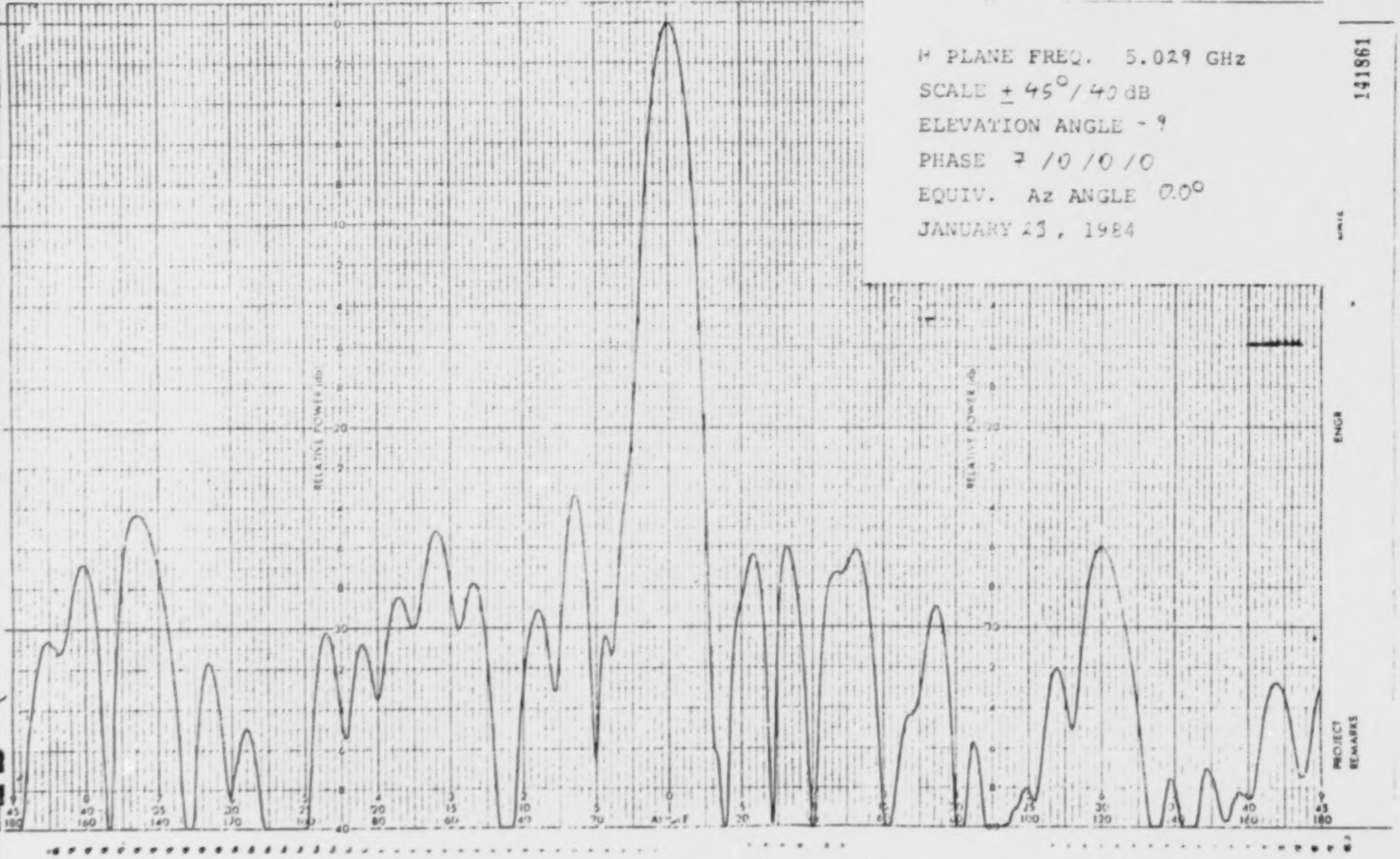


H PLANE FREQ. 5.029 GHz
SCALE ± 45°/ -0 dB
ELEVATION ANGLE - 7°
PHASE 7/0/0/0
EQUIV. Az ANGLE 0.0°
JANUARY 23, 1984

141839

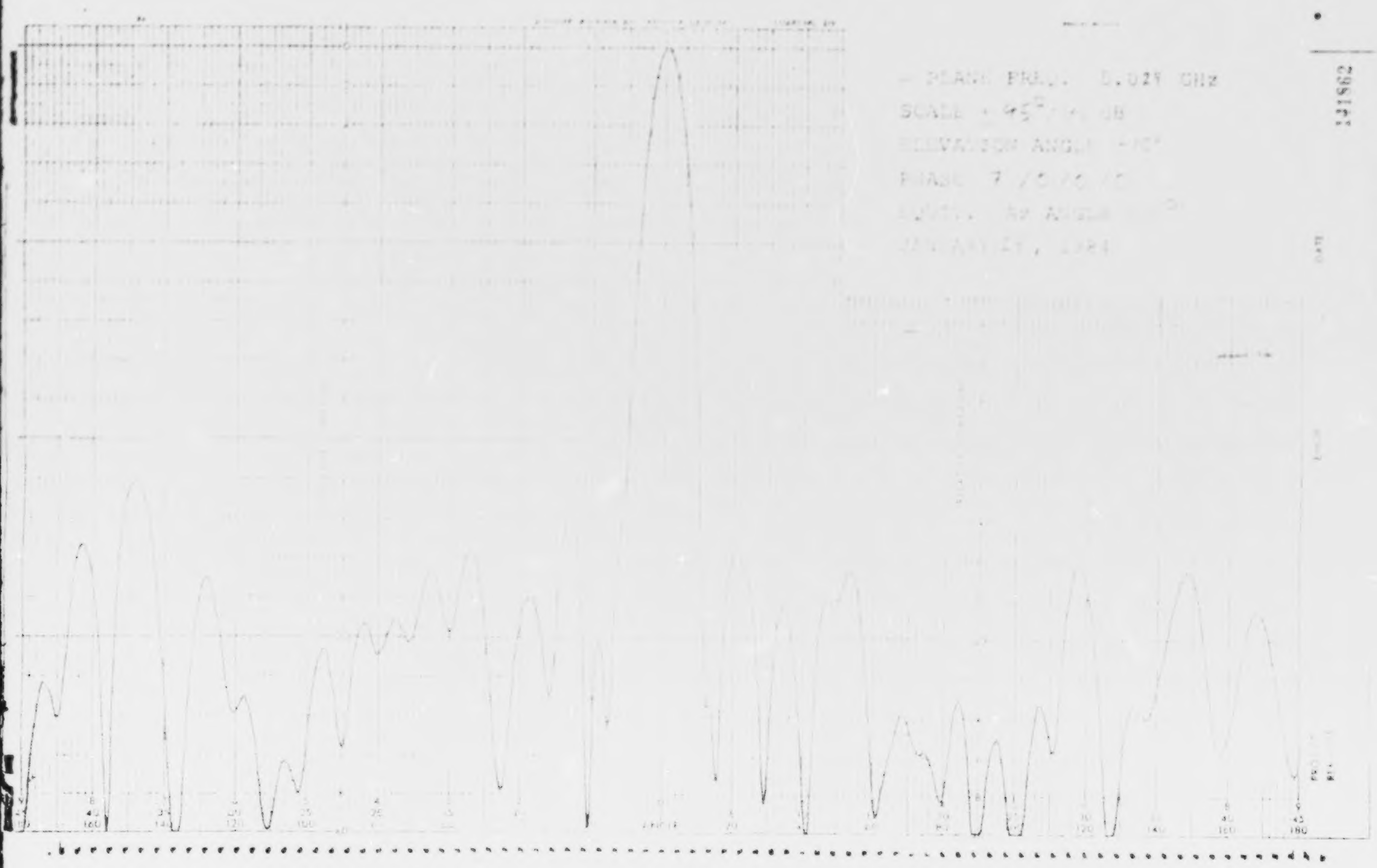


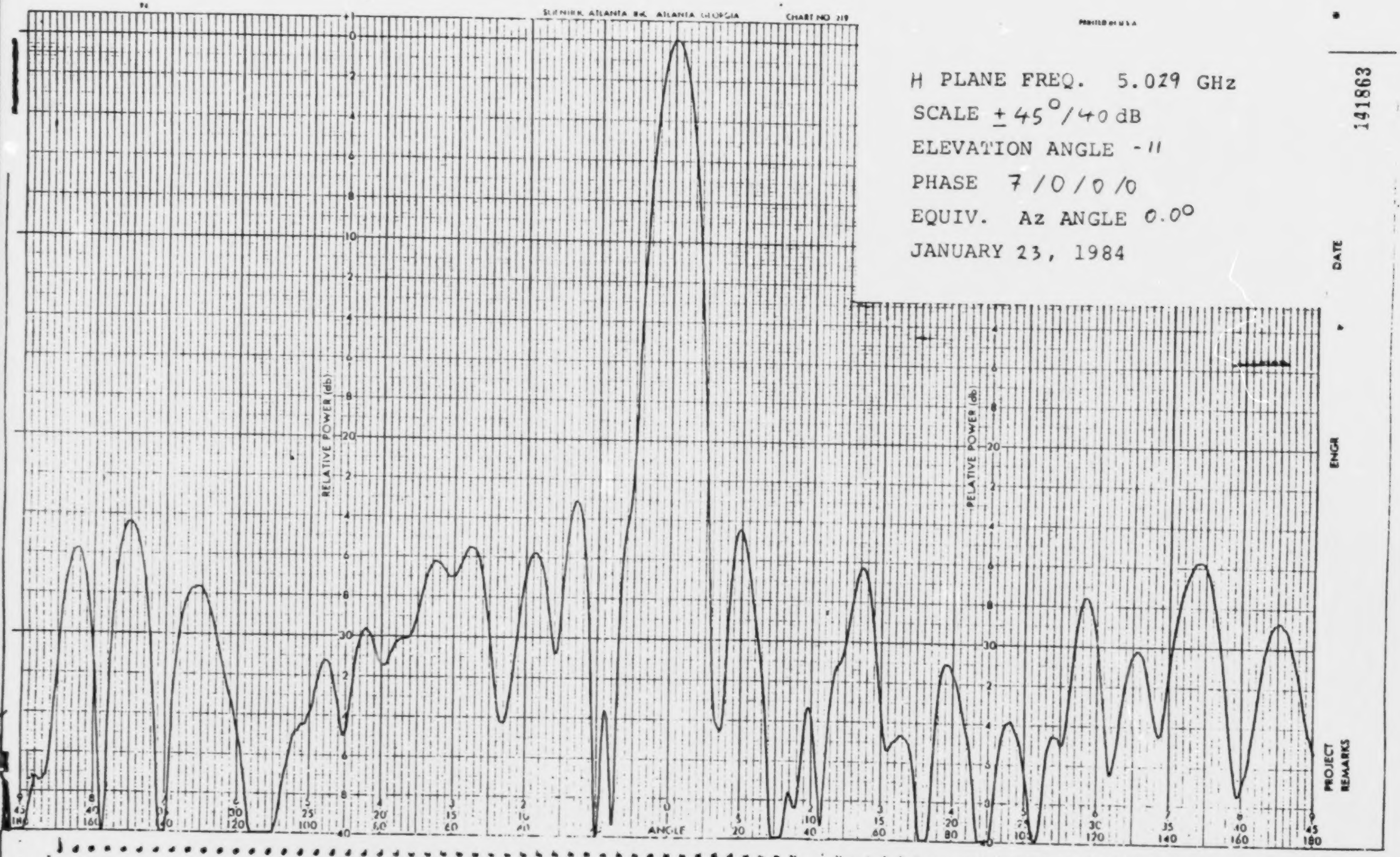
H PLANE FREQ. 3.029 GHz
SCALE ± 45°/40dB
ELEVATION ANGLE -8
PHASE 7/0/0/0
EQUIV. AZ ANGLE 0.0°
JANUARY 23, 1984



H PLANE FREQ. 5.029 GHz
SCALE ± 45°/ 40 dB
ELEVATION ANGLE - 9
PHASE 7 /0 /0 /0
EQUIV. Az ANGLE 0.0°
JANUARY 23 , 1984

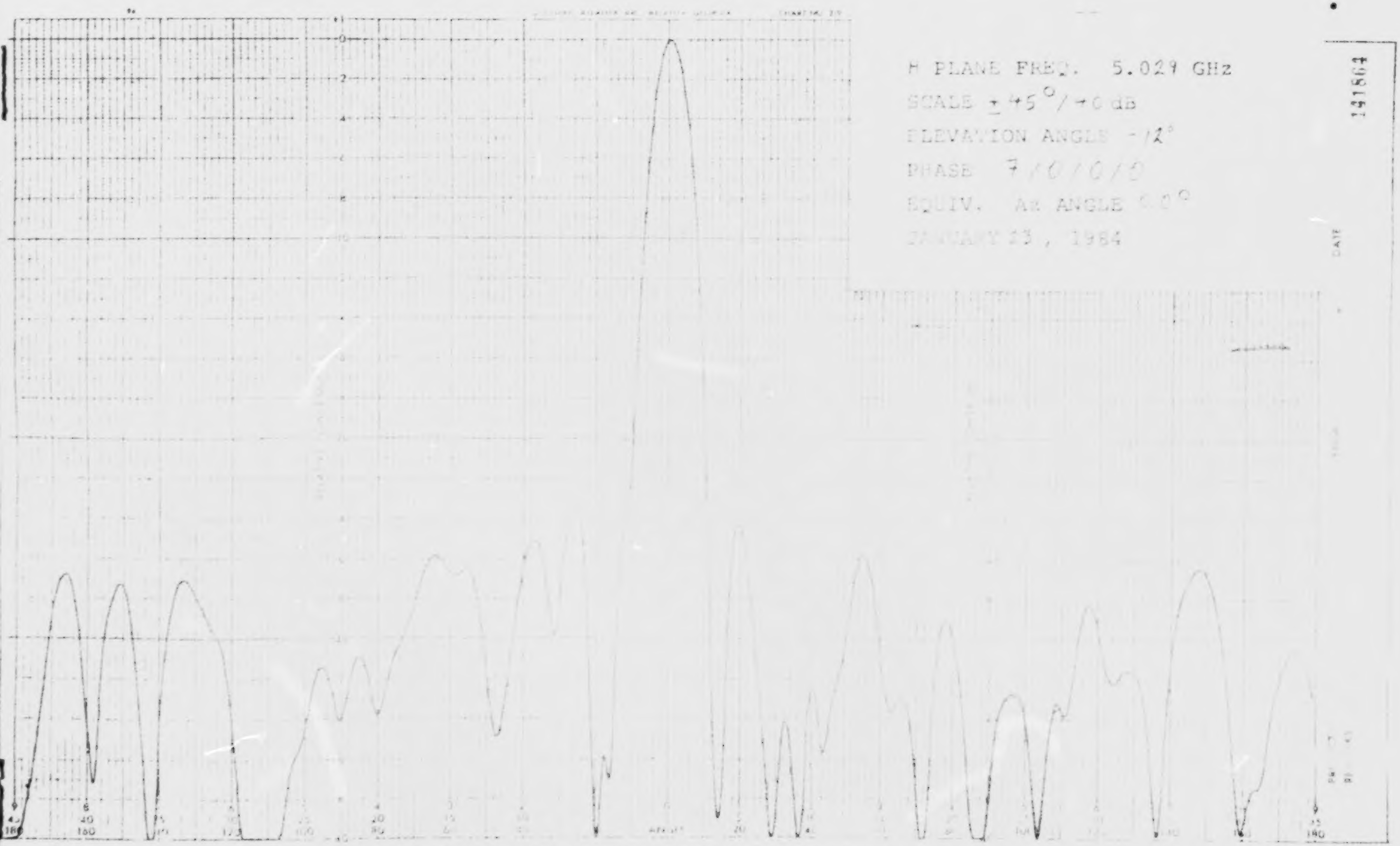
141861


PLANE FREQ. 5.025 GHz
SCALE ± 45°/ dB
ELEVATION ANGLE
PHASE 7/0/0/0
ANGLE
JANUARY 27, 1984
131862
CENTER
180
160
140
120
100
80
60
40
20
0
20
40
60
80
100
120
140
160
180

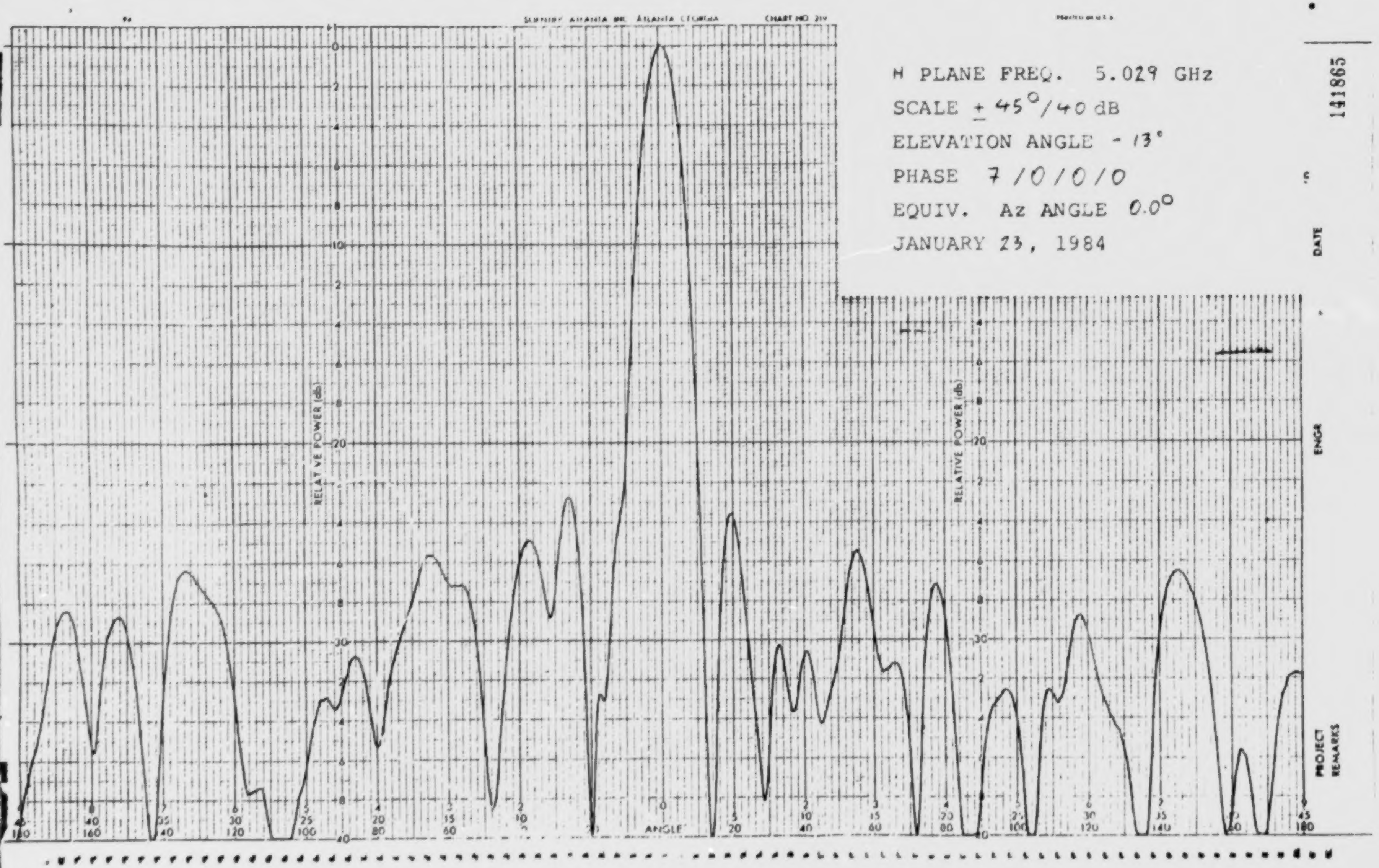


H PLANE FREQ. 5.029 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE -11
PHASE 7/0/0/0
EQUIV. Az ANGLE 0.0°
JANUARY 23, 1984

141863

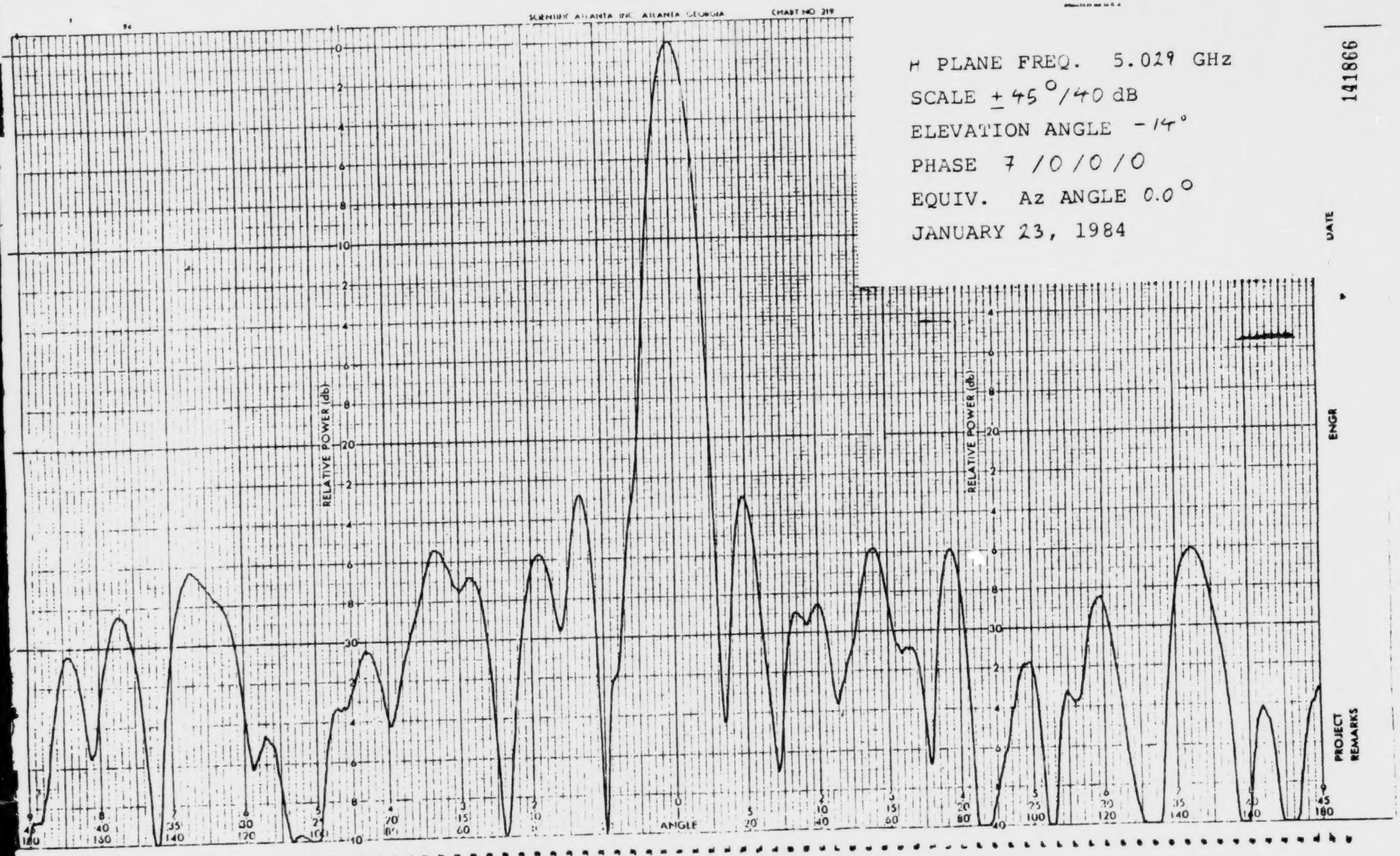


H PLANE FREQ. 5.029 GHz
SCALE ±45°/40 dB
ELEVATION ANGLE -12°
PHASE 7/0/0/0
EQUIV. Az ANGLE 0.0°
JANUARY 23, 1984



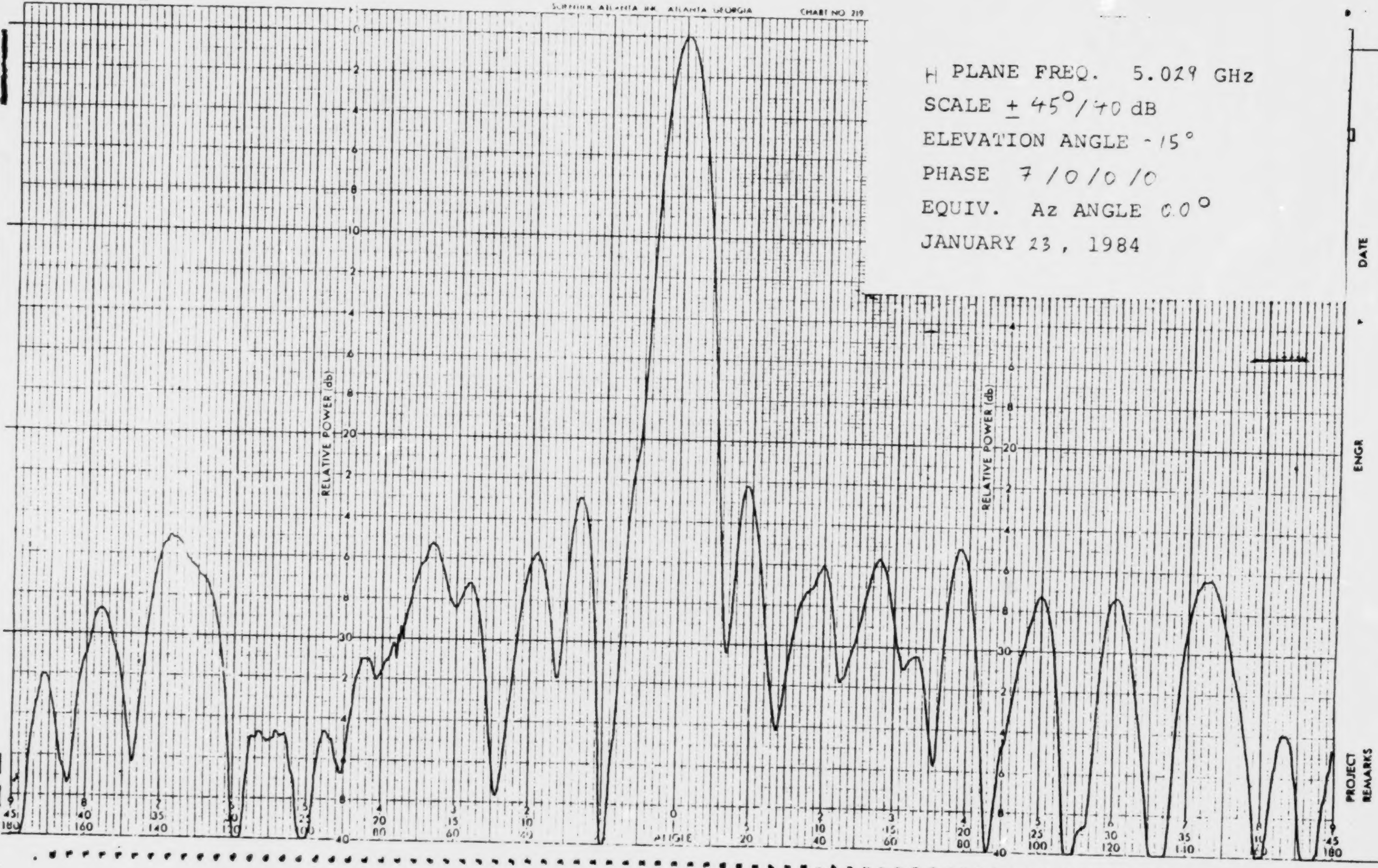
H PLANE FREQ. 5.029 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE - 13°
PHASE 7/0/0/0
EQUIV. Az ANGLE 0.0°
JANUARY 23, 1984

141865



H PLANE FREQ. 5.029 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE -14°
PHASE 7/0/0/0
EQUIV. Az ANGLE 0.0°
JANUARY 23, 1984

141866



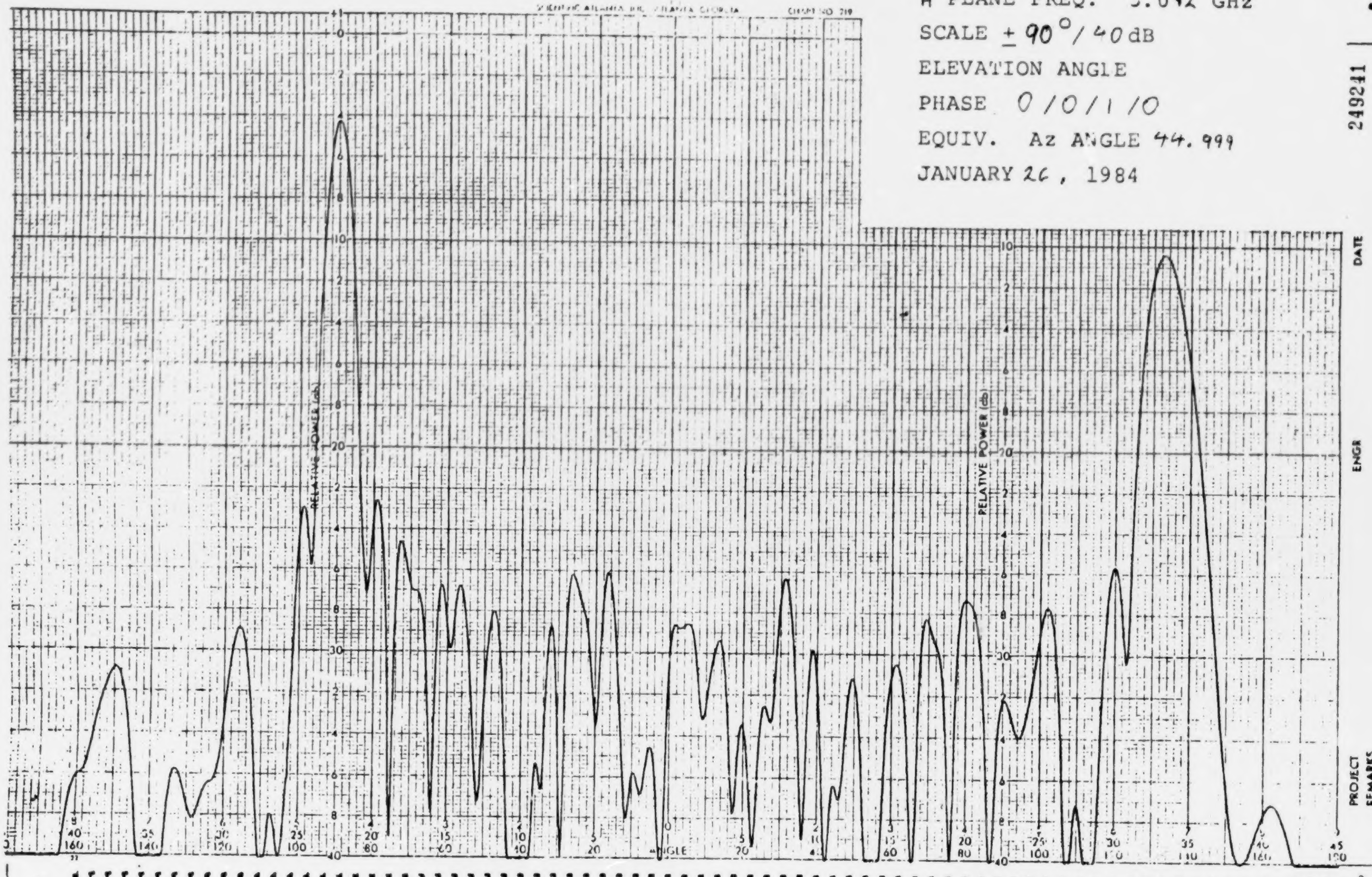
H PLANE FREQ. 5.029 GHz
SCALE ± 45°/40 dB
ELEVATION ANGLE -15°
PHASE 7/0/0/0
EQUIV. Az ANGLE 0.0°
JANUARY 23, 1984

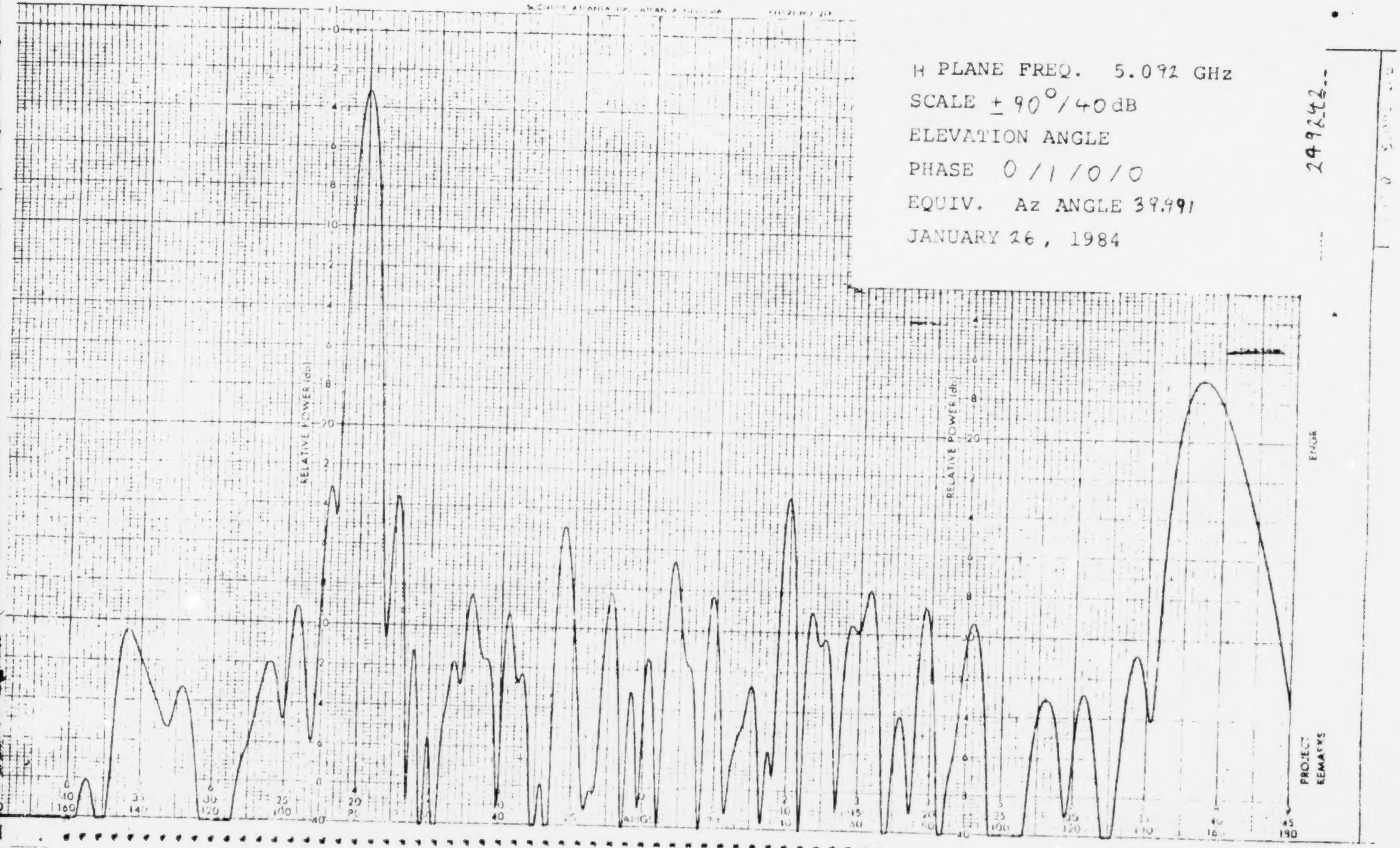
APPENDIX 6

Grating Lobes

H PLANE FREQ. 5.092 GHz
SCALE ± 90°/ 40 dB
ELEVATION ANGLE
PHASE 0/0/1/0
EQUIV. Az ANGLE 44.999
JANUARY 26, 1984

249241



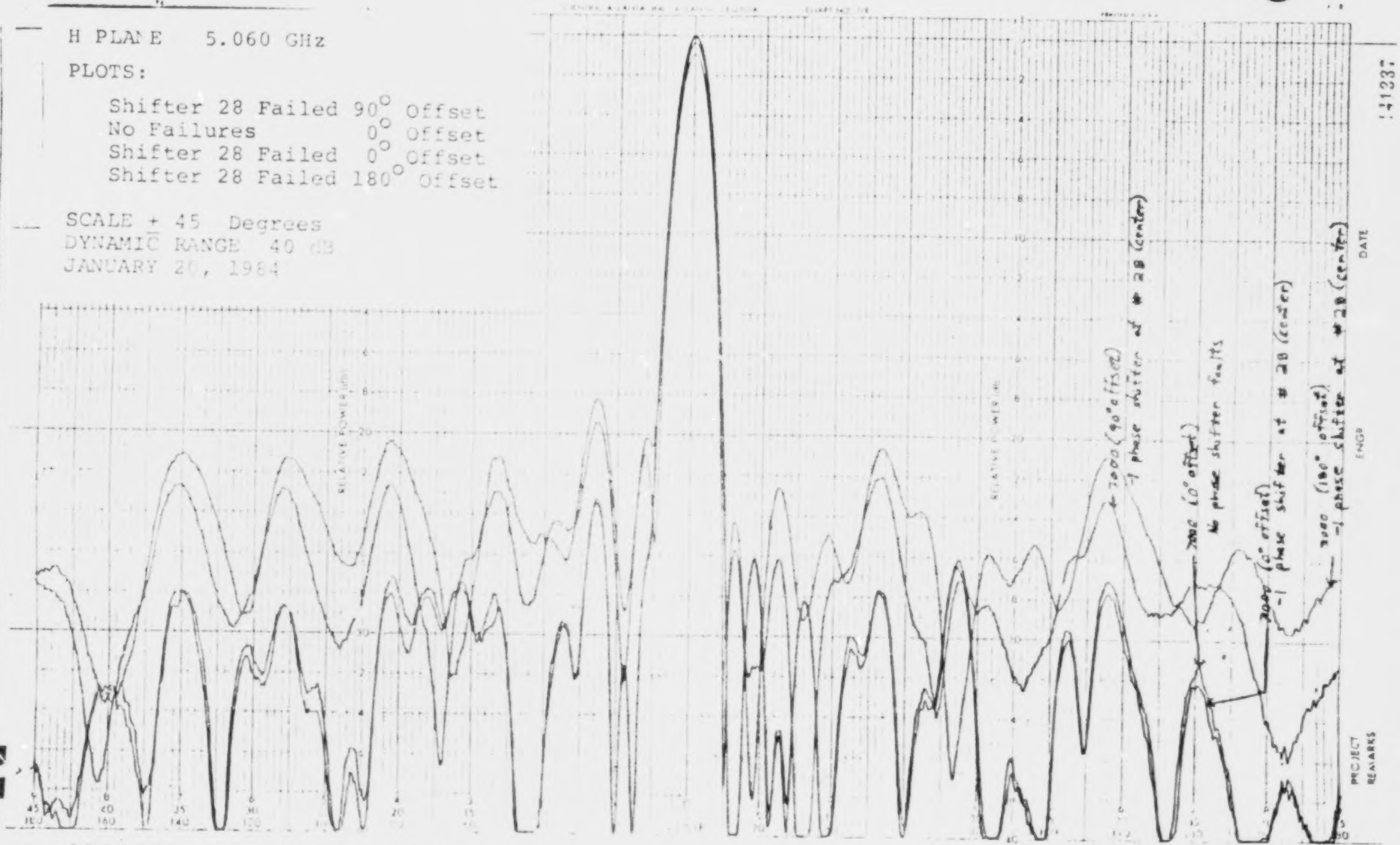


H PLANE FREQ. 5.092 GHz
SCALE ± 90°/40dB
ELEVATION ANGLE
PHASE 0/1/0/0
EQUIV. Az ANGLE 39.991
JANUARY 26, 1984

249242

APPENDIX 7

Phase Shifter Failures


H PLANE 5.060 GHz

PLOTS:

Shifter 28 Failed 90° Offset
No Failures 0° Offset
Shifter 28 Failed 0° Offset
Shifter 28 Failed 180° Offset

SCALE ± 45 Degrees
DYNAMIC RANGE 40 dB
JANUARY 20, 1984

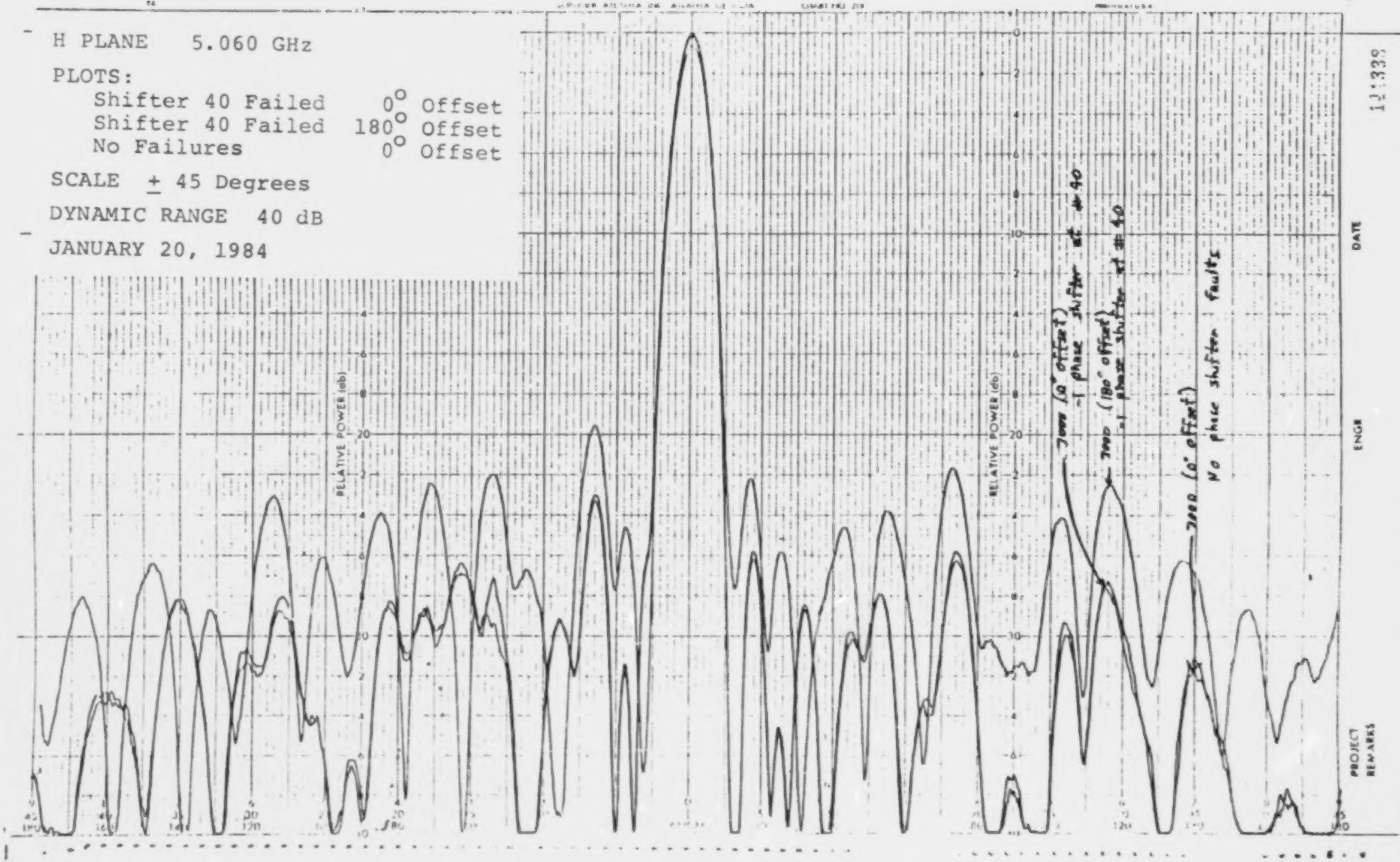
H PLANE 5.060 GHz

PLOTS:
  Shifter 40 Failed 0° Offset
  Shifter 40 Failed 180° Offset
  No Failures 0° Offset

SCALE ± 45 Degrees

DYNAMIC RANGE 40 dB

JANUARY 20, 1984



H PLANE 5.060 GHz

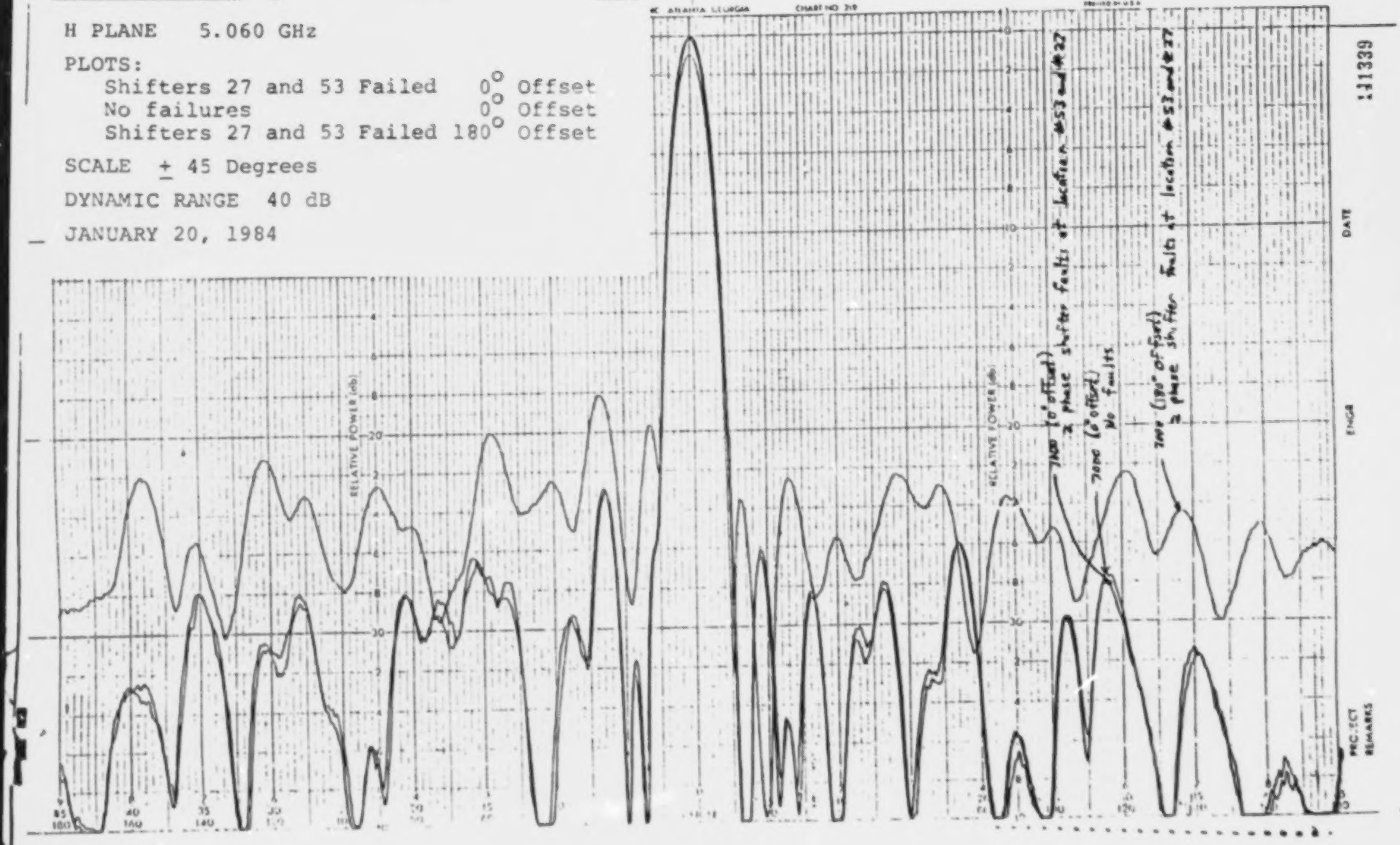
PLOTS:

Shifters 27 and 53 Failed	0°	Offset
No failures	0°	Offset
Shifters 27 and 53 Failed	180°	Offset

SCALE ± 45 Degrees

DYNAMIC RANGE 40 dB

JANUARY 20, 1984



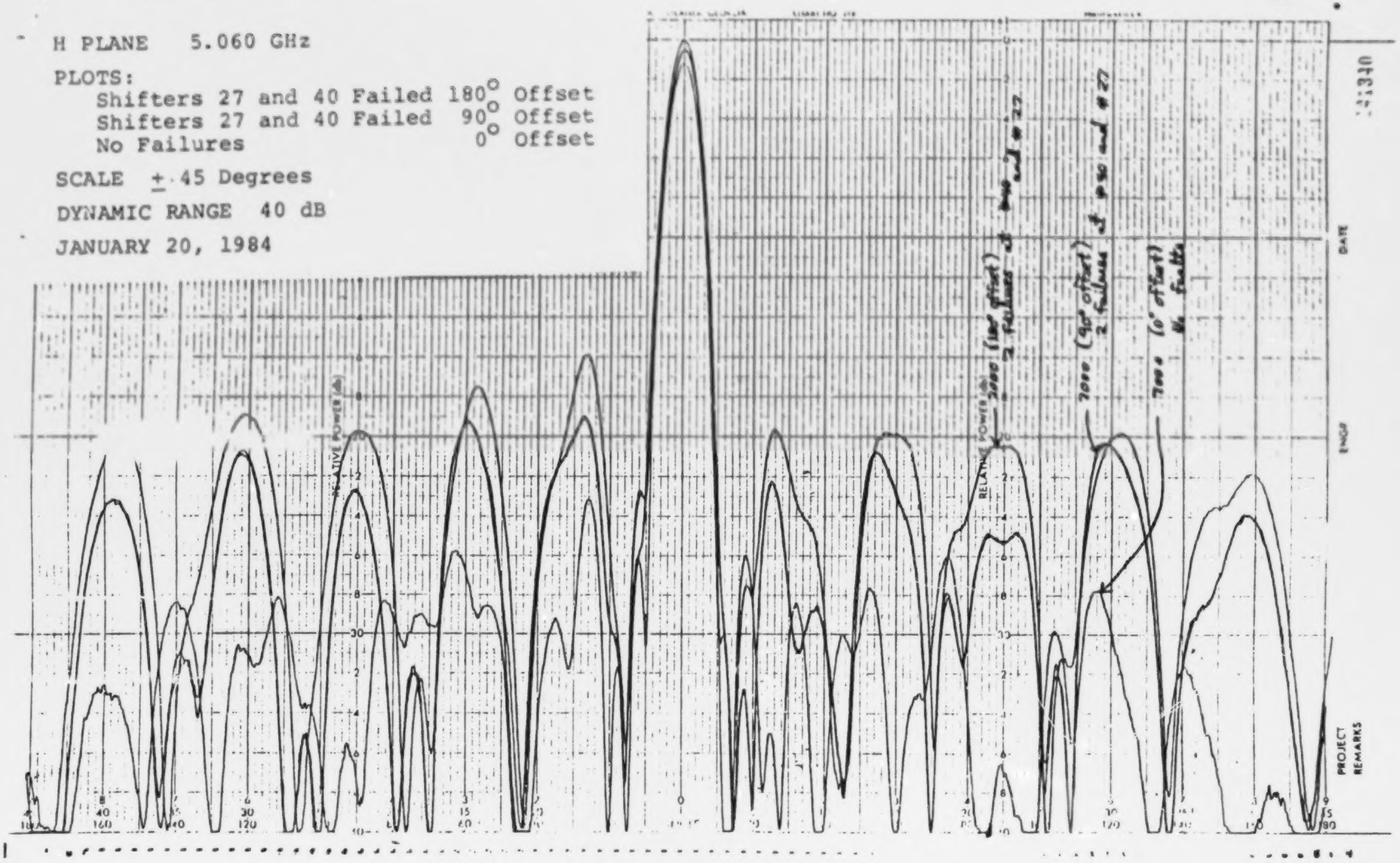
H PLANE 5.060 GHz

PLOTS:
Shifters 27 and 40 Failed 180° Offset
Shifters 27 and 40 Failed 90° Offset
No Failures 0° Offset

SCALE ± 45 Degrees

DYNAMIC RANGE 40 dB

JANUARY 20, 1984



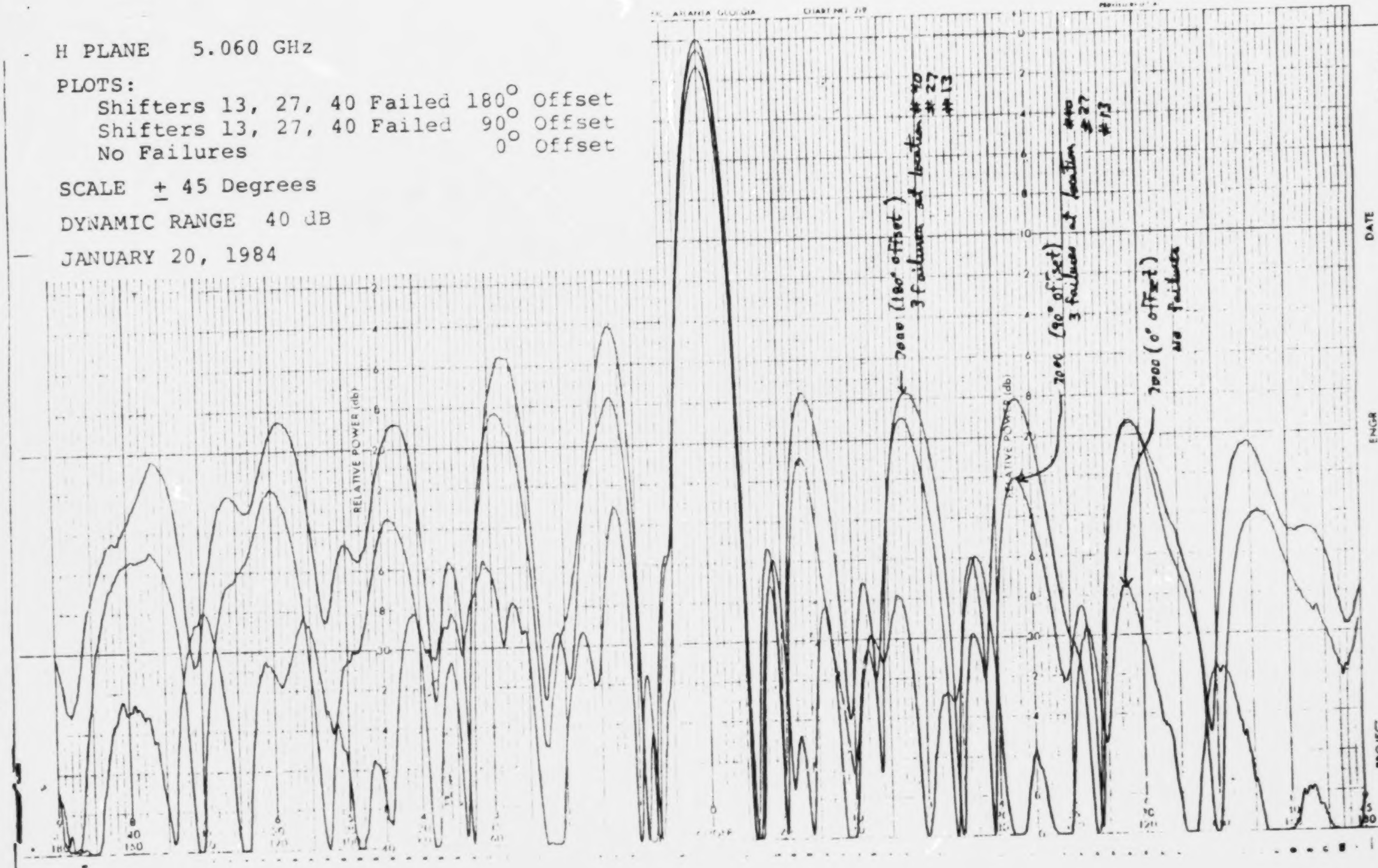
H PLANE 5.060 GHz

PLOTS:
  Shifters 13, 27, 40 Failed 180° Offset
  Shifters 13, 27, 40 Failed 90° Offset
  No Failures 0° Offset

SCALE ± 45 Degrees

DYNAMIC RANGE 40 dB

JANUARY 20, 1984



APPENDIX 8

CORPORATE FEED

Return loss/Forward loss

Measurements

FREQUENCY	RETURN LOSS S11		LOSS FORWARD S21		PORT
MHZ	DB	ANG	DB	ANG	#
5030.0	15.48	92.9	34.61	95.9	01
5060.0	14.16	48.6	33.29	27.2	
5090.0	13.44	10.3	31.17	-32.1	
5030.0	15.52	93.8	33.77	101.0	02
5060.0	14.17	48.9	32.54	27.8	
5090.0	13.46	10.5	30.91	-35.1	
5030.0	15.51	74.1	32.56	95.1	03
5060.0	14.17	48.7	31.69	26.9	
5090.0	13.45	10.8	30.24	-33.7	
5030.0	15.56	94.4	31.91	98.4	04
5060.0	14.20	48.7	30.82	25.7	
5090.0	13.49	10.9	29.68	-39.0	
5030.0	15.53	94.2	30.80	94.8	05
5060.0	14.21	48.5	30.02	22.3	
5090.0	13.49	10.7	29.18	-37.5	
5030.0	15.52	94.2	29.94	97.8	06
5060.0	14.16	48.4	29.03	24.8	
5090.0	13.46	10.8	28.09	-36.4	
5030.0	15.66	95.2	29.06	93.0	07
5060.0	14.29	48.8	27.61	22.2	
5090.0	13.54	10.8	26.53	-42.2	
5030.0	15.67	95.0	28.36	94.5	08
5060.0	14.33	48.6	26.81	23.4	
5090.0	13.55	10.6	25.58	-41.3	
5030.0	15.63	95.1	26.08	92.7	09
5060.0	14.25	49.0	25.82	22.1	
5090.0	13.53	10.9	25.91	-40.5	
5030.0	15.72	95.3	25.48	95.1	10
5060.0	14.33	48.9	25.10	24.9	
5090.0	13.58	10.7	25.04	-37.7	
5030.0	15.71	95.5	25.23	91.4	11
5060.0	14.35	49.1	24.46	20.7	
5090.0	13.59	10.6	24.28	-43.5	

FREQUENCY	RETURN LOSS		LOSS FORWARD		PORT
	S11		S21		#
MHZ	DB	ANG	DB	ANG	
5030.0	15.66	95.2	24.30	92.3	12
5060.0	14.33	48.8	23.75	20.9	
5090.0	13.59	10.6	23.51	-42.9	
5030.0	15.78	95.2	22.92	93.3	13
5060.0	14.34	48.7	22.74	21.4	
5090.0	13.59	10.4	22.56	-42.4	
5030.0	15.88	96.0	22.08	92.6	14
5060.0	14.45	49.1	21.94	20.8	
5090.0	13.64	10.4	21.70	-43.1	
5030.0	15.77	95.5	21.73	92.4	15
5060.0	14.40	48.8	21.52	21.9	
5090.0	13.64	10.3	21.25	-41.0	
5030.0	15.73	94.9	21.00	91.3	16
5060.0	14.33	48.6	20.77	20.5	
5090.0	13.60	10.3	20.46	-43.2	
5030.0	15.78	95.1	20.37	95.1	17
5060.0	14.34	48.7	20.67	23.2	
5090.0	13.60	10.2	21.16	-38.5	
5030.0	15.76	95.1	20.06	90.0	18
5060.0	14.34	48.8	20.30	17.9	
5090.0	13.60	10.2	20.75	-44.1	
5030.0	15.69	94.4	20.00	94.5	19
5060.0	14.27	48.5	20.05	22.2	
5090.0	13.58	10.2	20.30	-41.5	
5030.0	15.69	94.0	19.89	96.1	20
5060.0	14.27	48.4	19.83	22.5	
5090.0	13.62	9.8	19.95	-41.9	
5030.0	15.70	94.0	19.47	93.7	21
5060.0	14.26	48.2	19.56	21.1	
5090.0	13.61	9.8	20.00	-41.7	
5030.0	15.64	93.8	18.95	98.9	22
5060.0	14.26	48.0	19.15	25.4	
5090.0	13.62	9.7	19.55	-38.0	

FREQUENCY	RETURN LOSS S11		LOSS FORWARD S21		PORT #
MHZ	DB	ANG	DB	ANG	
5030.0	15.63	94.1	18.66	97.6	23
5060.0	14.26	48.2	18.85	25.7	
5090.0	13.65	9.8	19.20	-37.1	
5030.0	15.59	93.5	18.55	95.5	24
5060.0	14.25	47.8	18.85	23.6	
5090.0	13.66	9.5	19.23	-40.1	
5030.0	15.58	93.8	19.62	92.5	25
5060.0	14.24	47.6	19.38	23.3	
5090.0	13.72	9.2	19.85	-37.9	
5030.0	15.63	94.2	18.41	95.4	26
5060.0	14.25	47.8	18.27	26.3	
5090.0	13.75	9.1	18.90	-35.7	
5030.0	15.64	94.4	18.53	94.1	27
5060.0	14.31	47.9	18.28	23.5	
5090.0	13.81	9.1	18.45	-40.0	
5030.0	15.29	107.6	18.51	95.1	28
5060.0	13.15	55.9	18.24	25.0	
5090.0	13.35	8.5	17.53	-36.4	
5030.0	15.38	108.2	18.45	95.3	29
5060.0	13.20	55.7	18.50	24.7	
5090.0	13.35	8.6	18.15	-37.8	
5030.0	15.40	107.8	18.13	96.0	30
5060.0	13.19	55.3	18.50	26.5	
5090.0	13.33	8.7	18.35	-36.8	
5030.0	15.47	108.5	17.45	93.0	31
5060.0	13.13	56.0	17.60	23.9	
5090.0	13.22	8.6	17.60	-38.9	
5030.0	15.37	107.6	18.10	92.6	32
5060.0	12.98	55.9	18.26	24.7	
5090.0	13.14	8.6	18.35	-37.4	
5030.0	15.42	107.0	18.01	94.9	33
5060.0	13.13	55.2	18.15	24.0	
5090.0	13.26	8.7	18.10	-40.1	

FREQUENCY	RETURN LOSS S11		LOSS FORWARD S21		PORT
MHZ	DB	ANG	DB	ANG	#
5030.0	15.32	106.7	18.60	95.5	34
5060.0	13.06	55.0	18.75	23.5	
5090.0	13.21	8.8	18.61	-41.0	
5030.0	15.22	105.9	19.60	96.4	35
5060.0	13.06	55.0	19.55	23.5	
5090.0	13.18	8.8	19.10	-41.3	
5030.0	15.19	105.0	20.25	94.8	36
5060.0	12.99	54.4	19.95	23.1	
5090.0	13.15	8.7	19.55	-40.0	
5030.0	15.21	104.6	20.10	92.3	37
5060.0	13.01	54.4	20.11	23.1	
5090.0	13.18	8.6	20.05	-37.7	
5030.0	15.24	105.5	19.80	90.9	38
5060.0	13.06	54.8	19.90	24.1	
5090.0	13.23	8.3	20.09	-35.7	
5030.0	15.19	105.3	20.34	91.6	39
5060.0	13.06	54.8	20.50	23.7	
5090.0	13.24	8.1	20.30	-35.1	
5030.0	15.32	106.4	20.70	90.7	40
5060.0	13.19	55.3	20.85	23.0	
5090.0	13.36	7.5	20.70	-36.0	
5030.0	15.24	105.5	21.40	91.2	41
5060.0	13.07	55.0	21.75	21.6	
5090.0	13.34	7.7	21.67	-39.1	
5030.0	15.29	105.5	22.40	92.4	42
5060.0	13.12	55.1	22.70	21.7	
5090.0	13.39	7.5	22.55	-34.3	
5030.0	15.36	105.4	23.20	92.2	43
5060.0	13.17	54.9	23.25	22.6	
5090.0	13.40	7.1	23.24	-37.9	
5030.0	15.39	106.8	23.65	90.6	44
5060.0	13.26	55.8	23.79	22.0	
5090.0	13.49	7.0	23.85	-38.3	

FREQUENCY	RETURN LOSS S11		LOSS FORWARD S21		PORT #
MHZ	DB	ANG	DB	ANG	
5030.0	15.38	105.9	24.20	88.8	45
5060.0	13.19	55.5	24.69	21.3	
5090.0	13.45	6.8	25.12	-36.5	
5030.0	15.35	105.6	24.36	88.1	46
5060.0	13.19	55.5	25.23	21.1	
5090.0	13.47	6.8	25.88	-37.2	
5030.0	15.30	105.2	26.54	90.7	47
5060.0	13.12	55.1	25.77	23.5	
5090.0	13.45	6.9	25.12	-35.7	
5030.0	15.41	105.7	26.81	88.0	48
5060.6	13.19	55.4	26.31	21.6	
5090.0	13.50	6.6	25.85	-37.3	
5030.0	15.30	105.3	27.83	90.0	49
5060.0	13.13	55.3	27.75	20.7	
5090.0	13.46	6.8	27.52	-35.7	
5030.0	15.27	104.7	28.39	89.4	50
5060.0	13.12	55.2	28.50	20.4	
5090.0	13.46	6.6	28.48	-35.5	
5030.0	15.26	104.9	29.21	97.6	51
5060.0	13.13	55.3	28.94	24.9	
5090.0	13.47	6.6	28.74	-35.8	
5030.0	15.23	105.1	29.88	91.7	52
5060.0	13.09	55.8	30.06	21.8	
5090.0	13.50	6.8	29.95	-35.2	
5030.0	15.13	103.3	31.22	93.0	53
5060.0	13.01	55.1	30.97	20.0	
5090.0	13.41	6.8	30 80	-39.7	
5030.0	15.08	103.1	31.75	89.5	54
5060.0	13.01	55.1	31.74	19.5	
5090.0	13.41	6.8	31.18	-36.1	

APPENDIX 9

GROUND INSPECTION REPORT

SUMMARY SHEET

GROUND INSPECTION TESTS

TEST REFERENCE	DESCRIPTION	ANNEX 10 REFERENCE
G - 1	Station RF Frequency Accuracy	3.11.4.1.3
G - 2	Station RF Frequency Jitter	3.11.4.1.3
G - 3	D.P.S.K. Phase Shift	3.11.4.4.3.1
G - 4	Scanning Beamwidth and Shape	3.11.5.2.1
G - 5	Dynamic Sidelobes	G.M. Section
G - 6	Function Timing (Sequence)	3.11.4.3.4
G - 7	Function Timing (Internal)	3.11.4.3.5
G - 8	Function Rates	3.11.4.3.3
G - 9	Function Preambles	3.11.4.4
G - 10	Basic Data Coding	3.11.4.8.2
G - 11	Facility Identification (MORSE)	3.11.4.6.2.1
G - 12	Interference	3.11.4.1.4

Test Ref: G - 1

Parameter: Station R.F. Frequency Accuracy

Equipment: Fluke 1953A Frequency Counter
Bendix MLS Receiver

Procedure:

We do not presently have the capability to measure the RF frequency directly. The exciter used in our system uses a 48 times multiplier which requires us to measure the reference frequency and use the receiver to confirm that the multiplier is on the correct harmonic.

The frequency counter is attached to the reference frequency output on the exciter and is set for 10 sec averaging.

A number of samples are taken at 15 min intervals to ensure that the driftover time is within spec.

The required stability of ± 10KHz represents ± 208Hz of the reference frequency.

Results:

Time	Reference Frequency (MHz)	Calculated RF Output (MHz)
1200	105.437468	5060.9985
1215	105.437472	5060.9987
1230	105.437475	5060.9988
1245	105.437475	5060.9988
1300	105.437475	5060.9988
1315	105.437475	5060.9988
1330	105.437474	5060.9988
1345	105.437475	5060.9988
1400	105.437476	5060.9988

MLS receiver operation was confirmed on channel 600.

Tolerance: Operating frequency must be less than plus or 10KHz from the assigned station frequency.
Ref. ICAO ANNEX 10: 3.11.4.1.3

Pass/Fail: Pass, meets ICAO Standard.

Test Ref: G - 2

Parameter: Station R.F. Frequency Jitter

Equipment: Fluke 1953A Frequency Counter
Bendix MLS Receiver

Procedure:

We do not presently have the capability to measure the RF frequency directly. The exciter used in our system uses a 48 times multiplier which requires us to measure the reference frequency and use the receiver to confirm that the multiplier is on the correct harmonic.

The frequency counter is attached to the reference frequency output on the exciter and is set for 1 sec averaging.

The display was observed for approximately 100 samples or 100 seconds.

Results:	Reference Frequency (MHz)	Calculated RF Output (MHz)
	Alternates between	Alternates between
	105.437512	5061.000576
	and	and
	105.437513	5061.000624

MLS receiver operation was confirmed on channel 600.

Tolerance: Frequency must not deviate more than plus or minus 50Hz from the nominal frequency when measured over a one second interval.
Ref. ICAO ANNEX 10: 3.11.4.1.3

Pass/Fail: Pass, meets ICAO Standard.

Test Ref.: G - 3

Parameter: DPSK Phase Shift

Equipment:
HP8743A Reflection Transmission Test Unit
HP8412A Phase-Magnitude display
HP1611A Logic State Analyzer
Oscilloscope

Procedure:

RF reference frequency for the reflection transmission test unit is taken from the unmodulated exciter output.

The amplifier monitor port is fed into the transmission return port on the test unit.

Phase shift is measured by using the Logic State Analyzer to stop the ECSM* microprocessor at a time when the ID antenna is turned on. The phase shifter state is controlled manually.

Measurements of phase are made on the phase magnitude display (reading accuracy ± 2°).

The transition time is determined by measuring the bias voltage to the PIN diode in the phase shifter. Both the ON and OFF transition times are recorded.

Results:

Phase Shift	180°	
Transition time	positive edge	200nS
	negative edge	100nS

Tolerance:
The DPSK Phase Shift shall be 180° plus or minus 10°.
Ref. ICAO ANNEX 10: 3.11.4.4.3.1
The phase transition shall be completed in 10 microseconds.
Ref. FAA STD 0226, 4.1.5.2

Pass/Fail: Pass, Meets ICAO and FAA Standards.

---

*Executive Controller System Monitor

Test Ref.: G - 4

Parameter: Scanning Beamwidth and Shape

Test Equipment: Bendix MLS Receiver
Oscilloscope

Procedure:

The receiver is set up approximately 1200ft from the array on boresight.

Receiver antenna is a horn approximately 16ft off the ground.

On the Oscilloscope the time between the -3dB points and between the -10dB points on the beam are measured.

The scale factor on the oscilloscope is 12dB/Volt which gives -3dB points 0.25 Volts below beam peak and -10dB points 0.83 Volts below the peak.

Results:

-Beam is symmetrical to beam center.
-time between -3dB points 94us
-time between -10dB points 164us
-time from beam center to -10dB points is 82us
-The measurement accuracy is ± 5us

Tolerance: The beamwidth for a nominal 2 degree beamwidth azimuth site on boresight shall be 2 degrees plus or minus 10% (90 to 110 microseconds)

The -10dB points on the beam shall be 0.7 to 0.9 Beamwidths from beamcenter. (70 to 90 microseconds for a 2 degree Beamwidth System). Ref. ICAO ANNEX 10 3.11.5.2.1.3

Pass/Fail: Pass, meets ICAO Standards.

Test Ref.: G - 5

Parameter: Dynamic Sidelobes

Test Equipment: Bendix MLS Receiver
Oscilloscope

Procedure:

The receiver is set up every 5° from -35° to +35° at distances ranging from 1200 to 2500 feet from the azimuth system.

The receiver antenna is a 16dB standard gain horn located about 16 feet above ground level.

On the oscilloscope the main beam peak is measured and the peak sidelobes are measured. The difference between the two readings gives the peak sidelobe levels. Calibration factor is 10dB/Volt on the oscilloscope.

Results:

Angle Relative To Azimuth (degrees)	Worst Case Peak Sidelobe (dB ref. beam peak)
+35	20
+30	22
+25	20
+20	20
+15	22
+10	21
+ 5	18
0	22
- 5	22
-10	22
-15	22
-20	21
-25	19
-30	18
-35	17

Tolerances:

Dynamic Sidelobes cannot persist above a level which is -10db down from the scanning beam mainlobe.
Ref. ICAO ANNEX 10 : 3.2

Pass/Fail: Pass, meets ICAO Standards.

Test Ref. : G - 6

Parameter: Function Timing (Sequence)

Equipment: Bendix ML 20A MLS Receiver
Tektronix Digital Oscilloscope

Procedure:

The receiver was set up on boresight 1500ft from the azimuth site with a omni-directional antenna mounted on a 12ft tower.

The Log Video from the receiver was connected to the scope as well as the High Rate Az Sync. A cursor was moved to each event on the wave form and the digital display of the cursor position was recorded.

Results:

See Table 13

Tolerance:

The function timing must follow the sequence given in ICAO ANNEX 10 Figures I-3B and I-3C.

Ref.: ICAO ANNEX 10 Attachment I 2.1.4

Pass/Fail: Pass, meets ICAO Standards.

Table 13

Function Timing

Function	Start Time(ms) Predicted	Measured
Sync Pulse	0	0
App. Az.	7.36	7.36
Basic Data 1,3-6,8	22.36	22.36
App. Az.	31.66	31.66
App. Az.	49.16	49.16
App. Az.	92.26	92.26
Basic Data 2	104.16	104.16
App. Az.	119.16	119.16
App. Az.	136.66	136.65
App. Az.	165.76	165.77
Basic Data 1,3-6,8	180.76	180.76
App. Az.	196.06	196.06
App. Az.	207.56	207.56
App. Az.	230.66	230.66
Basic Data 2	242.56	242.56
App. Az.	257.56	257.56
App. Az.	275.06	275.06
App. Az.	316.16	316.17
Basic Data 1,3-6,8	331.16	331.17
App. Az.	340.46	340.47
App. Az.	357.96	357.97
App. Az.	382.06	382.07
Basic Data 2	393.96	393.97
App. Az.	408.96	408.97
App. Az.	426.46	426.47
App. Az.	462.56	462.57
Basic Data 1,3-6,8	477.56	477.57
App. Az.	486.86	486.87
App. Az.	504.36	504.37
Aux. Data	533.86	533.87
App. Az.	546.46	546.47
Basic Data 2	558.36	558.37
App. Az.	573.36	573.37
App. Az.	590.86	590.87
Sync.	608.60	608.60

Test Ref.: G-7

Parameter: Function Timing (Internal)

Test Equipment: Fluke 1953A Frequency Counter

Procedure:

It is not possible at present to measure the internal timing of each function accurately in an "on-line" mode. However, the timing of each component can be checked by stopping the ECSM microprocessor at each step and using a counter to check the value loaded into system's timer. This test was performed for all functions during software validification tests. Correct operation of the ECSM is ensured by checking every timing pulse produced against that of the second ECSM.

The accuracy of the timing pulses is controlled by the system clock which can be measured while the system is operating.

Results:

- Measured Clock frequency	999.998KHz

Tolerance: The components within each function must have their timing maintained within plus or minus 2 microsec.

Ref.: ANNEX 10: 3.11.4.3.5
APPENDIX A, Tables A-1 to A-6

Pass/Fail: Pass, meets ICAO Standards.

Test Ref: G -8

Parameter: Function Rates

Equipment: Fluke 1953A Frequency Counter

Procedure:

The function rate for the azimuth is determined by connecting the counter to the azimuth trigger point and measuring the frequency over a 10 second average.

The function rate for Back Azimuth was also determined in the above manner, with the station configured as a back azimuth site.

For basic data words the maximum time between transmissions can be determined from the data gathered in test number IG-6.

Results:

Function	Frequency
High Rate Azimuth	39.4Hz
Back Azimuth	6.6Hz

Basic Data Word	Max. Time Between Transmission (mS)
1	311.8
2	154.4
3	5939.6
4	5939.6
5	5939.6
6	1529.0
7	767.0
8	5939.6

Tolerance:
High Rate Azimuth: 39+ 1.5 Hz
Back Azimuth : 6.5± 0.25 Hz
Basic Data 1: < 400 ms
" " 2: < 160 ms
3: < 10 sec
4: < 10 sec
5: < 10 sec
6: < 10 sec
7: < 1 sec
8: < 10 sec

Pass/Fail: Pass, meets ICAO Standards.

Test Ref.: G - 9

Parameter: Function Preambles

Equipment: Storage Oscilloscope

Procedure:

The trigger point for each function in turn is used to trigger the oscilloscope.

One channel on the oscilloscope is connected to the DPSK data output, the other to the transmission clock (15.625KHz) as a reference.

The bit patterns are recorded in their non-differential form (ie transitions are recorded as ones).

The preamble for back azimuth and basic data word 7 are recorded with the station configured as a back azimuth site.

Results: See Table 14
Indirectly Confirmed by MLS Receiver Operation

Tolerance:

Preamble coding must consist of a carrier acquisition period, a reference time code and a function identifier as specified in ICAO ANNEX 10 3.11.4.4.3.3

Ref: ANNEX 10 : 3.11.4.4

Pass/Fail: Pass, meets ICAO Standards.

Table 14 Preamble Codes Measured

				Basic Data Word							
CLOCK PULSE	BIT	AZ	BK AZ	1	2	3	4	5	6	7	8
1		0	0	0	0	0	0	0	0	0	0
2		0	0	0	0	0	0	0	0	0	0
3		0	0	0	0	0	0	0	0	0	0
4		0	0	0	0	0	0	0	0	0	0
5		0	0	0	0	0	0	0	0	0	0
6		0	0	0	0	0	0	0	0	0	0
7		0	0	0	0	0	0	0	0	0	0
8		0	0	0	0	0	0	0	0	0	0
9		0	0	0	0	0	0	0	0	0	0
10		0	0	0	0	0	0	0	0	0	0
11		0	0	0	0	0	0	0	0	0	0
12		0	0	0	0	0	0	0	0	0	0
13	I1	1	1	1	1	1	1	1	1	1	1
14	I2	1	1	1	1	1	1	1	1	1	1
15	I3	1	1	1	1	1	1	1	1	1	1
16	I4	0	0	0	0	0	0	0	0	0	0
17	I5	1	1	1	1	1	1	1	1	1	1
18	I6	0	1	0	0	1	1	1	0	1	1
19	I7	0	0	1	1	0	0	1	0	1	0
20	I8	1	0	0	1	1	0	0	0	1	1
21	I9	0	1	1	1	0	0	1	1	0	0
22	I10	1	0	0	0	0	1	1	1	0	1
23	I11	0	0	0	0	0	0	0	0	1	1
24	I12	0	1	0	0	0	0	0	1	0	1

Test Ref: G - 10

Parameter: Basic Data Coding

Equipment: Storage Oscilloscope

Procedure:

The trigger point for each data word in turn is used to trigger the oscilloscope.

One channel on the oscilloscope is connected to the DPSK data output, the other to the transmission clock (15.625KHz) as a reference.

The bit patterns are recorded in their non-differential form (ie transitions are recorded as ones).

The data coded in each word follows the results.

Basic Data Word 7 is recorded with station configured as a back azimuth site.

Results:

The bit patterns for each word including preambles, were as shown in Table 15. The words were coded as follows:

Basic Data 1

Approach azimuth to threshold distance	1100m
Approach azimuth proportional coverage limit	-40°
Approach azimuth proportional coverage limit	+40°
Clearance signal type	Scanning Beam

Basic Data 2

Ground Equipment Performance Level	not used
Minimum Glide Path	2.0°
Back Azimuth next function	no back azimuth
DME status	not used

Basic Data 3

Approach azimuth beamwidth	2.0°
Approach elevation beamwidth	not used
Flare elevation beamwidth	not used

Basic Data 3 (con't.)

Approach azimuth sector guidance alert

-60° to -20°	1°
-20° to -5°	1°
+20° to +5°	1°
+60° to +20°	1°

Basic Data 4

DME distance	not used
DME offset	not used

Basic Data 5

Approach azimuth antenna offset	OM (+)
DME or DME/P	not used
DME channel	not used

Basic Data 6

MLS ground subsystem identification	
Character 2	P
Character 3	A
Character 4	A

Basic Data 7

Ground equipment performance level	not used
Back azimuth antenna distance	600m
Back azimuth proportional coverage limit	-40°
Back azimuth proporation coverage limit	+40°
Back azimuth beam width	2°

Basic Data 8

Elevation antenna height	not used
Elevation antenna offset	not used
MLS datum point to threshold distance	not used

Table 15 **BASIC DATA WORD CODES**

	BASIC DATA WORD							
BIT	1	2	3	4	5	6	7	8
I1	1	1	1	1	1	1	1	1
I2	1	1	1	1	1	1	1	1
I3	1	1	1	1	1	1	1	1
I4	0	0	0	0	0	0	0	0
I5	1	1	1	1	1	1	1	1
I6	0	0	1	1	1	0	1	1
I7	1	1	0	0	1	0	1	0
I8	0	1	1	0	0	0	1	1
I9	1	1	0	0	1	1	0	0
I10	0	1	0	1	1	1	0	1
I11	0	0	0	0	0	0	1	1
I12	0	0	0	0	0	1	0	1
I13	1	0	1	0	0	0	0	0
I14	1	0	1	0	0	1	0	0
I15	0	0	0	0	0	1	0	0
I16	1	0	0	0	0	0	1	0
I17	0	0	0	0	0	1	1	0
I18	0	0	0	0	0	1	0	0
I19	1	0	0	0	0	1	0	0
I20	1	0	0	0	0	1	1	0
I21	1	0	0	0	0	0	1	0
I22	1	0	0	0	0	0	1	0
I23	0	0	0	0	0	0	1	0
I24	1	0	0	0	0	0	1	0
I25	1	0	0	0	0	1	1	0
I26	1	0	0	0	0	1	1	0
I27	1	0	0	0	0	0	1	0
I28	0	0	0	0	0	0	1	0
I29	1	0	0	0	0	0	0	0
I30	0	0	0	0	0	0	0	0
I31	0	0	0	0	0	0	1	0
I32	0	0	1	0	0	0	0	0

TABLE 2 - Basic Data Word Codes

Tolerance: The Basic Data Coding must follow the format given in ICAO ANNEX 10 APPENDIX A Table A-7.
Ref. ICAO ANNEX 10 3.11.4.8.2

Pass/Fail: Pass, meets ICAO Standards.

Test Ref: G - 11

Parameter: Facility Identification-Morse Code

Equipment: Bendix MLS Receiver
Storage Oscilloscope

Procedure:

The oscilloscope is connected to the receiver audio output.

The coding of ID signal is recorded.

The length of the a dot, dash, symbol space and character space is measured.

The repetition rate is measured.

Results:

Coding: MPAA

—— —•— —• • - •—

Times measured

Dash	.45 sec.
Dot	.13 sec.
symbol space	.13 sec.
character space	.51 sec.
repetition interval	7 sec.

Tolerance: Repetition Rate is not less than 6 times per minute

Dots Duration		0.13 to 0.16 sec
Dashes Duration		0.39 to 0.48 sec
Symbol Space	15	1 DOT ± 10%
Character Space	15	greater than 3 DOTS

REF: ICAO ANNEX 10 3.11.4.6.2.1

Pass/Fail: Pass, meets ICAO Standards.

Test Ref: G - 12

Parameter: Interference

Equipment: HP8559A Spectrum Analyzer

Procedure:

The spectrum analyzer is attached to each output (Az and ID) of the antenna switch (just before the antenna).

The analyzer is set up for the finest resolution bandwidth (in this case 1KHz).

The frequency span per division is set to 500KHz/div.

The time per division is 5 sec.

Results:

Figures 46 and 47

Tolerance: The Transmitted signal shall be such that during the transmission time the mean power density above a height of 600 metres shall not exceed $-100.5 dBW/M^2$ for angle guidance and -95.5 dBW/M^2 for data, as measured in a 150 KHz band width centred 840 KHz or more from the nominal frequency.

Knowing the Azimuth Antenna radiation pattern maximum limits referenced to the nominal frequency peak amplitude were calculated to be.

Azimuth Antenna -29 dB at 690KHz or more from carrier
ID Antenna -40 dB at " " " " "
Ref: ANNEX 10: 3.11.4.1.4

Pass/Fail: Pass, meets ICAO Standards.

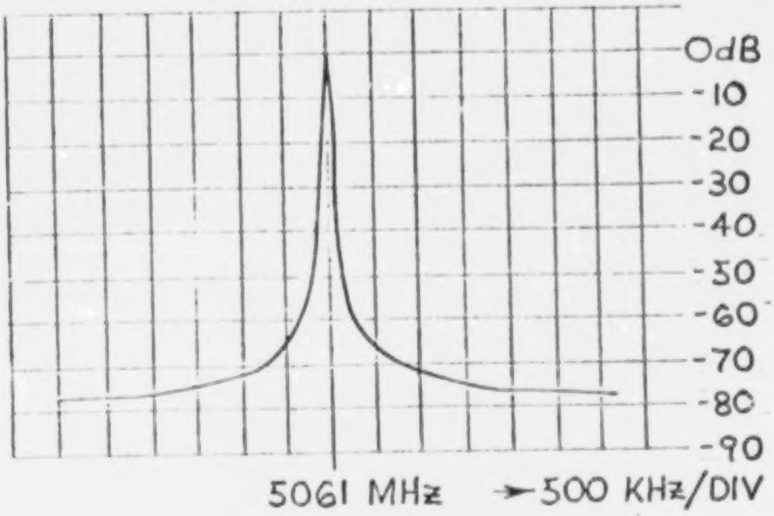


Figure 46 - Azimuth Antenna Spectrum

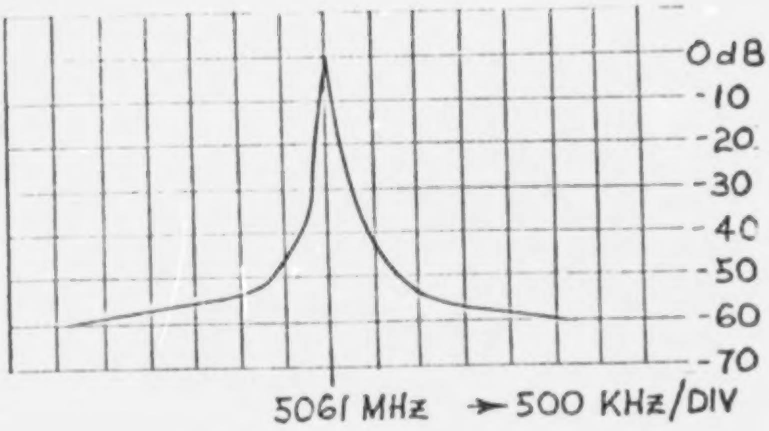


Figure 47 - ID Antenna Spectrum
(Hard phase shift)

APPENDIX 10

FLIGHT INSPECTION REPORT

MLS FLIGHT TEST PLAN

Type of Run: Azimuth Alignment

Objective: To verify the Azimuth system 0 degree radial is aligned with the runway centreline

Receiver Angle Setting:
AZ 0 degree
EL N/A

Aircraft Flight Path: Centreline approach from 12 nautical miles to threshold maintaining a 2500 feet AGL altitude. Tracking with theodolite to start at 10 Nmi and continue until rate of increase of vertical angle becomes unacceptable or 0.5 Nmi from ground station.

Recorded Parameters:

RAW Cross Pointer	RCP
Corrected Cross Pointer	CCP
Receiver Flag	FLAG
Theodolite	THEO
DME distance	DME

Type of Run: Azimuth Level Crossovers

Objective: To determine the coverage of off centre-line radials within the proportional coverage limits of ± 40 degrees and to assess the accuracy of the selected radial course.

Receiver Angle Setting: AZ 0, ± 2, ± 10, ± 20, ± 30, ± 38 degrees

EL N/A

Aircraft Flight Test: Start approach from 12 Nmi out and fly toward the transmitter at a constant altitude of 2500 feet AGL along each of above 11 different radials specified above. Theodolite tracking to start at 10 Nmi and continuing until rate of increase of vertical angle becomes unacceptable or 0.5 Nmi from ground station.

Recorded Parameters:
RCP
CCP
FLAG
THEO
DME

Type of Run:	Azimuth Coverage Probe
Objective:	To determine coverage limit of the azimuth system
Receiver Angle Setting:	AZ 0 Degree EL N/A
Aircraft Flight Path:	Start run at a distance of 40Nmi (using map reference) on centreline radial at altitude of 2500 feet AGL. Fly at constant altitude along the centreline radial noting the distance at which signal is acquired and continue to fly until 0.5 Nm from ground station.
Record Parameters:	RCP CCP FLAG THEO DME

NOTE: Record any loss of flag after signal acquisition.

Type of Run:	Azimuth Coverage Arc
Objective:	To determine coverage limit is in excess of 20 Nmi minimum for azimuth system. Indirect confirmation of signal strength.
Receiver Angle Setting:	AZ 0 degrees EL N/A
Aircraft Flight Path:	Start run at a distance of 25 Nmi from ground station and fly an arc from -50 degrees to +50 degrees using Sydney VORTAC. Event every 5 degrees based on TACAN. A constant altitude of 2500 feet shall be maintained.
Recorded Parameters:	RCP CCP FLAG DME Event every 5 degrees.

NOTE: If receiver flags appear during arc from -40 degrees to +40 degrees repeat at 20 Nmi distance.

Type of Run: Guidance Parameter Check

Objective: To verify that there is uniform guidance information throughout the coverage area.

Receiver Angle Setting:
AZ see Recorded Parameters.
EL N/A

Aircraft Flight Path: Start run at a distance of 5 Nmi from ground station and fly an arc from -50 degrees to +50 degrees maintaining a constant distance from transmitter. Maintain a constant altitude of +1500 feet AGL throughout.

Recorded Parameters:
RCP
CCP
FLAG
THEO
DME
Event at ± 35 degrees
Event at ± 25 degrees
Event at ± 15 degrees
Event at ± 5 degrees

Select Azimuth angles on receiver of -35, -25, -15, -5, +5, +15, +25 and +35 degrees prior to angle event blips. Reselect next angle after obtaining full scale deflection on CDI.

NOTE: Start tracking with theodolite -40 degrees and finish +40 degrees.

Type of Run: Simulated Approach

Objective: To verify acceptable operation of azimuth ground equipment on standard type approach.

Receiver Angle Setting:
AZ 0 degrees
EL N/A

Aircraft Flight Path: Start run at 12Nmi from ground station and track with theodolite in bound from 10Nmi as long as practical. Pilot to fly 3 degrees descent angle starting at 10Nmi to ground station.

Recorded Parameters:
RCP
CCP
FLAG
THEO
DME

FLIGHT TEST SUMMARY - Azimuth MLS

RUN NUMBER	TYPE		LOCATION		
1	Level	Crossover	0 Deg.	2500' AGL	12Nmi
2	"	"	+38 "	"	"
3	"	"	+30 "	"	"
4	"	"	+20 "	"	"
5	"	"	+10 "	"	"
6	"	"	+2 "	"	"
7	"	"	0 "	"	"
8	"	"	-2 "	"	"
9	"	"	-10 "	"	"
10	"	"	-20 "	"	"
11	"	"	-30 "	"	"
12	"	"	-38 "	"	"
13	"	"	0 "	2500' AGL	40Nmi
14	Coverage	Arc	-50 to +50 Deg.	2500' AGL	25Nmi
15	Coverage	Arc	-50 to +50 Deg	1500' AGL	5Nmi
16	Simulated	APP	0 Deg.	3^{o} EL	12Nmi

Glossary of Terms

aperture - an opening through which radiation can pass

beamwidth - the angular width of the beam measured in azimuth between points of half power intensity.

bit - a single character that corresponds to on and off conditions

delta insertion loss - (1) maximum insertion loss incurred between bits in a phase shifter at any state

(2) maximum insertion loss incurred between phase shifters in any state

dielectric - A material that has poor electric conductivity. It undergoes polarization when subjected to an electric field.

dielectric constant - the property of the material that determines how much electrostatic energy can be stored per unit volume when unit voltage is applied

directional horn - a horn antenna that receives energy from a specific direction

flange - a fitting used at the end of a waveguide to provide connection to another transmission path

I.D. antenna - the antenna located external to the enclosure transmitting information to the aircraft MLS receiver

insertion loss - the loss in load power due to the insertion of a component or device in the transmission line irriditing - the process of dipping the aluminium metal in a chromate corrosion protective fluid.

phase - the position of a point on a waveform from 0 to 360 degrees

phase shifter - a device that changes the phase relationship between two signals.

power divider - a device that produces a desired distribution of power at a branch point

radiation pattern - a graphical representation of the radiation of the antenna as a function of direction

radiator - each of the waveguides that emit energy into space

radome - A protective housing for the antenna made from dielectric material that is transparent to RF energy

RMS error - the effective phase error of all the bits in a phase shifter

Sidelobe - a lobe of energy outside the specified radiation pattern

Slot - an opening on the waveguide through which radiation can pass.

Sputtering - a process of depositing a metal on a nonmetal substrate

standing wave - a wave in which the amplitude at a specific point does not very with time

substrate - the physical material on which the micro circuit is fabricated (duriod)

Taylor distribution - a mathematical series representing an ideal radiation pattern travelling wave - a wave formed by translation of energy along a conductor

VSWR - voltage standing wave ratio. The ratio of the amplitude of the electric field or voltage at a voltage minimum to that at an adjacent maximum in a transmission line

Waveguide - a rectangular metal tube designed to guide or conduct high frequency electromagnetic waves through its interior

List of Abbreviations

Az - Azimuth

BSC - Beam Steering Controller

CW - Continous Wave

dB - Decibel

dBm - Decibel above 1 milliwatt

DME - Distance Measuring Equipment

DOT - Department of Transport

DPSK - Differentially Coherent Phase - shift

FAA - Federal Aviation Administration

ICAO - International Civil Aviation Authority

I.D. - Identification

ILS - Instrument Landing System

MHz - Mega hertz

min - Minute

MLS - Microwave Landing System

mm - Millimeter

MOT - Ministry of Transport

MTTR - Mean time to repair

RF - Radio Frequency

RMS - root mean square

STOL - Short take off and landing

TRSB - Time referenced scanning beam

VSWR - Voltage Standing Wave Ratio

BIBLIOGRAPHY

Balonis, C.A. "Antenna Theory, Analysis and Design"
Harper and Row
1982

Canadian Astronautics Limited "Report on a Microwave Landing System Antenna"
November 1983

Canadian Astronautics Limited "Report on Phase II Microwave Landing System Antenna"
March 1983

Canadian Astronautics Limited "The Final Report For An Azimuth Microwave Landing System"
February 1984

Edwards, T.C. "Foundations For Microstrip Circuit Design"
John Wiley and Sons
1981

Federal Aviation Administration "Microwave Landing System Ground Equipment" FAA-E-2721/ 1a, 2a, 3b, 4a, 5a
October 1983

CA1
DTC801
84
M34
c.2

Federal Aviation Administration "Microwave Landing System (MLS)
Interoperability and Performance Requirements"
FAA-STD-022b
October 1983

Hughes Aircraft Company "Antenna conceptual Design Study"
May 1981

International Civil Aviation Organization "Aeronautical
Telecommunications"
July 1972

Porad, L.I. and Moynihan R.L. "Split-Tee Power Divider"
IEEE Transactions on Microwave Theory and Techniques
September 1964

White, J.F. "Diode Phase Shifters For Array Antennas"
IEEE Transactions on Microwave Theory and Techniques
February 1974

Library [illegible] Centre /
[illegible] (GSLA)
[illegible] LE
[illegible] 1985
[illegible] Canada

Library [illegible] Centre
[illegible] 1984
[illegible] Transport Canada

TP 5520E

MICROWAVE LANDING SYSTEM
AZIMUTH ANTENNA SUBSYSTEM
SUMMARY REPORT

by

M. McAloney

M. Senechal

M. Tough

J. Whyte

Micronav Limited
Sydport Industrial Park
Sydney, Nova Scotia

June 1984

Egalement disponible en français

The contents of this report reflect the views of the contractor and not necessarily the official views or policies of the Transportation Development Centre.

PROJECT TEAM

The project team for Micronav Limited was composed of :

Mr. J. Currie

Mr. M. McAloney

Mr. M. Tough

Mr. J. Foote

and others.

REPORT DOCUMENTATION FORM

1 Transport Canada Report No
TP5520E

2 TDC Project No.
4977

3 Recipient's Catalogue No

4 Title and Subtitle
MICROWAVE LANDING SYSTEM AZIMUTH ANTENNA SUBSYSTEM
SUMMARY REPORT

5 Report Date
June 1984

6 Performing Organization Report No

7 Author(s)
M. McAloney, M. Senechal, M. Tough, J. Whyte

8 Transport Canada File No
D1455-153-2

9 Performing Organization Name and Address
Micronav Limited
Sydport Industrial Park
P.O. Box 1523
Sydney, Nova Scotia B1P 6R7

10 DSS File No
07SC. T8200-2-2599

11 DSS or Transport Canada Contract No
0SC83-00093

12 Sponsoring Agency Name and Address
Transportation Development Centre (TDC)
1000 Sherbrooke St. West, Suite 2421
Montreal, Quebec H3A 2R3

13 Type of Report and Period Covered
Summary May/83-May/84

14 Sponsoring Agency Code
4977

15 Supplementary Notes
Summary of Microwave Landing System Azimuth Antenna Subsystem (TP5519E)

16 TDC Project Officer
Micha Avni

17 Abstract

This summary report briefly describes a project to develop and construct an azimuth antenna for a microwave landing system. A feasibility study demonstrated the use of a fully filled array of 54 slotted waveguide radiators, 4-bit phase shifters and a power divider feed network. Individual components were fabricated, evaluated and redesigned as required. A prototype azimuth antenna was constructed and extensively tested on an antenna range. The antenna was integrated with control electronics and a microwave source. Ground and flight testing of the system confirmed compatibility with standard avionics receiving equipment to international standards.

18 Key Words
Azimut, phased array, waveguide, phase shifters, power divider

19 Distribution Statement
A limited number of copies available from sponsoring agency.

20 Security Classification (of this report)
Unclassified

21 Security Classification (of this page)
Unclassified

22 No of Pages
23

23. Price
Nil

FORMULE DE DOCUMENTATION POUR RAPPORT

1. Nº du rapport Transports Canada TP5520E	2 Nº de l'etude – CDT 4977	3 Nº de catalogue du destinataire

4. Titre et sous-titre
MICROWAVE LANDING SYSTEM AZIMUTH ANTENNA SUBSYSTEM
RAPPORT SOMMAIRE

5 Date du rapport
Juin 1984

6 Nº du rapport de l'organisme executant

7 Auteur(s)
M. McAloney, M. Senechal, T. Tough, J. Whyte

8 Nº de dossier Transports Canada
D1455-153-2

9 Nom et adresse de l'organisme executant
Micronav Limited
Sydport Industrial Park
Case postale 1523
Sydney, Nouvelle Ecosse B1P 6R7

10 Nº de dossier – ASC
07SC.T8200-2-2599

11 Nº de contrat – ASC ou Transports Canada
0SC83-00093

12. Nom et adresse de l'organisme parrain
Centre de développement des transports (CDT)
1000, rue Sherbrooke ouest
Bureau 2421
Montréal (Québec) H3A 2R3

13 Genre de rapport et periode visee
Sommaire Mai/83-Mai/84

14 Code de l'organisme parrain
4977

15 Remarques additionnelles
Sommaire de "Microwave Landing System Azimuth Antenna Subsystem (TP5519E)

16 Agent de projet – CDT
Micha Avni

17 Resume

Ce rapport décrit sommairement la mise au point et la construction d'une antenne à balayage azimutal pour système d'atterrissage hyperfréquence (MLS). Une étude a démontré la faisabilité d'un réseau comportant 54 radiateurs en guides d'ondes à fentes, des déphaseurs 4 bits et un réseau d'alimentation à répartiteur de puissance. Les composants ont été fabriqués, évalués et modifés selon les besoins. Un prototype d'antenne à balayage azimutal a été construit et testé de façon approfondie sur un terrain d'essai. Des circuits de commande et une source hyperfréquence étaient incorporés à l'antenne. Des essais au sol et en vol ont permis de vérifier que le système est conforme aux normes internationales pour le matériel de réception standard utilisé en avionique.

18. Mots-clés
Azimut, réseau à commande de phase, guide d'ondes, déphaseur, répartiteur de puissance

19 Diffusion
Une nombre limité de copies est disponible auprès de l'organisme parrain

20. Classification de securite (de ce rapport) non-classifié	21. Classification de securite (de cette page) non-classifiée	22 Nombre de pages 23	23 Prix nil

CDT/TDC 79-005

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the assistance provided by the personnel of Canadian Astronautics Limited, Hughes Aircraft Company, and especially Meyer Associates of Boston, Mass.

FOREWORD

This report summarizes the development of an antenna subsystem used for azimuth scanning in a microwave landing system (MLS). It was carried out by Micronav Limited for the Transportation Development Centre to be used with Micronav's MLS control electronics.

The primary objectives of the program were:

a. Carry out a preliminary design.

b. Demonstrate the feasibility of the proposed design.

c. Develop and construct a MLS Azimuth Antenna Subsystem.

d. Carry out detailed testing in Ottawa, in house at Micronav, and located next to a runway at Sydney Airport.

The purpose of this contract is to establish in Canada MLS expertise which will exploit the enormous potential national and international market.

The microwave landing system provides an aircraft with the capability for precision approach and landing through the use of sophisticated microwave and computer technology. The azimuth system, which provides the horizontal coverage, consists of two overall subsystems; the antenna itself and the control electronics.

The antenna system electronically sweeps a narrow beam thoughout the coverage area to provide high precision positioning information to approaching aircraft. Radio Frequency (RF) energy is distributed from a single microwave source via a corporate feed or power divider to a series of 54 phase shifters and radiating elements. The phase shifters are digitally controlled by the elctronics to determine a specific phase distribution across the face of the array.

A separate waveguide, located near the bottom of the other 54 waveguides, provides monitoring signals permitting an enhanced maintenance capability.

TABLE OF CONTENTS

PAGE

1. INTRODUCTION 1

    1.1 General 1
    1.2 Background 1

2. ANTENNA SYSTEM DESIGN

    2.1 System Requirements 4
    2.2 Functional Description 5
    2.3 Microwave Source 6
    2.4 Corporate Feed 8
    2.5 Phase Shifters 8
    2.6 Phased Array 9

3. TESTING AND RESULTS 11

4. CONCLUSIONS 12

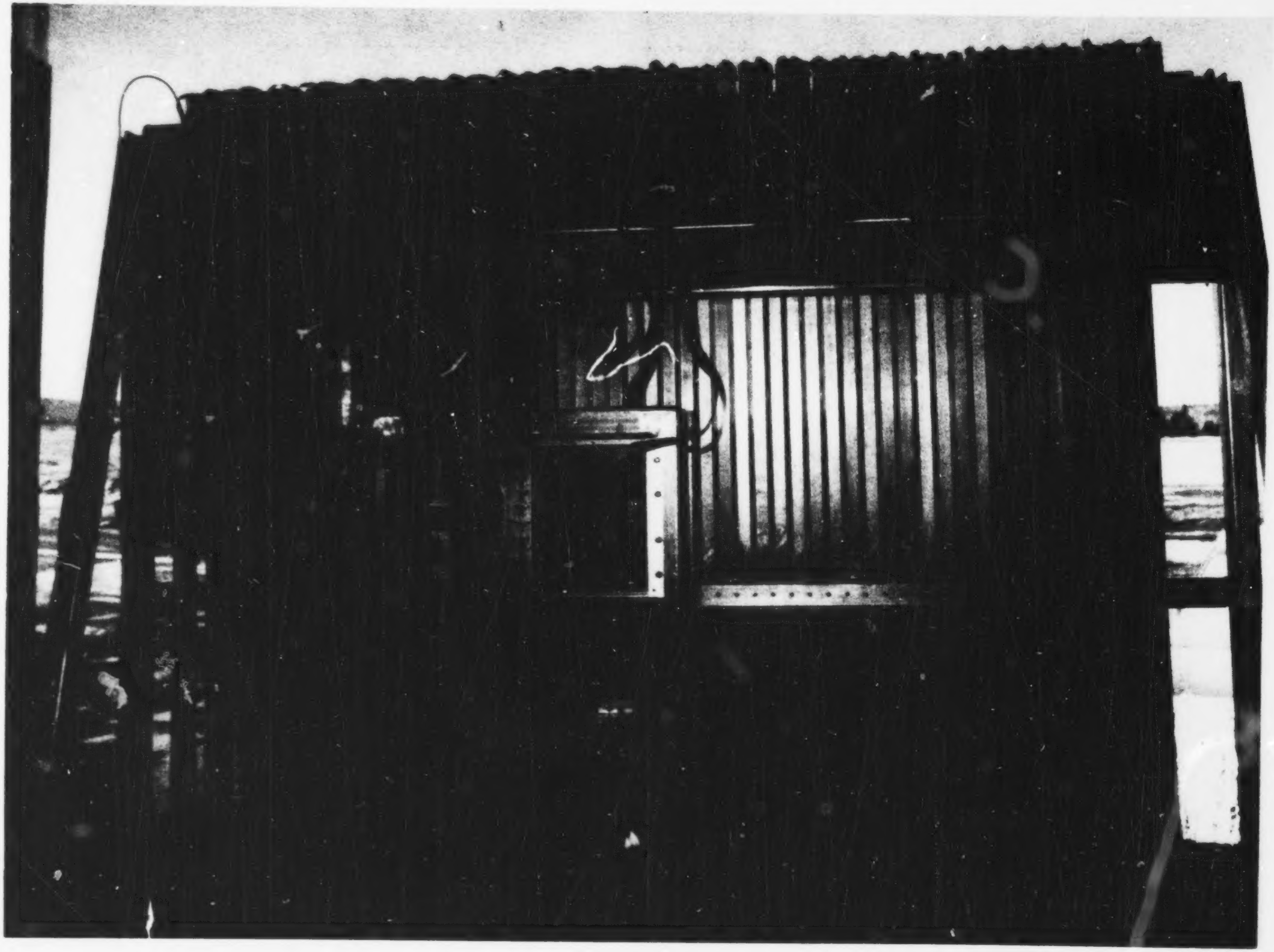
LIST OF FIGURES

Figure 1 MLS Azimuth Antenna Operation 2

Figure 2 System Block Diagram 7

LIST OF TABLES

Table 1 MLS Azimuth Antenna Design Specifications 4



MLS Azimuth Antenna System with Control Electronics (Rear View)

1. INTRODUCTION

1.1 General

In May of 1983, the Transportation Development Centre contracted Micronav Limited to develop and construct a Microwave Landing System Azimuth Antenna. This subsystem is to be used in conjunction with the control electronics previously designed.

With the sucessful completion of the azimuth antenna, a major milestone has beeen reached in the design of an all Canadian MLS.

1.2 Background

The purpose in using a landing system is to provide the personnel of an aircraft, preparing to land, guidance information relating the airplane's position to that of the runway and desired glide path. Presently, Instrument Landing System (ILS), developed during World War II, is used. It uses two fixed radio beacons which originated from large antennas located near the runway. A receiver installed in an aircraft cockpit receives these radiated beams, deriving fly left or right and angle of descent information. Instrument Landing Systems are limited in that only one approach path is provided regardless of aircraft type or other criteria. They are expensive to install, dependent on site terrain, and offer only 40 separate channels.

The Microwave Landing System (MLS) has been selected by the International Civil Aviation Organization as the world wide standard for aircraft landing guidance. Under the ICAO plan, Instrument Landing Systems will be replaced by MLS over a period of 10 years commencing in 1985.

The MLS has several inherent advantages that make it the system of the future thereby forcing ILS into retirement. They are:

a. Improved performance and precision.

b. Ability to serve new locations such as mountainous areas and oil rigs.

c. Improved safety.

d. Multiple approach paths for helicopters, normal, and STOL fixed wing aircraft.

e. 200 channels available.

f. Aircraft fuel savings due to shorter approach routes and reduced stacking.

g. Minimal site preparation.

h. Capability of automatic landings.

i. Inexpensive installation.

j. Greatly reduced terrain dependence.

The contractor for this project, Micronav Limited, was incorporated in December 1980 to pursue the development of a Microwave Landing System. Presently, an azimuth system is in operation and an elevation antenna is under development. Subcontracts were given to Hughes Aircraft Company for a preliminary design feasibility study and to Canadian Astronautics Limited for antenna design and construction.

The function of the azimuth antenna is to transmit a 2° beam which scans "TO" and "FRO" at a constant rate of 20,000°/sec between coverage limits of ±40° from the runway centerline. A MLS receiver located on board an aircraft measures the length of time between a beam passing in one direction and then returning in the opposite direction. The sweep from left to right with respect to an incoming aircraft id known as the "TO" scan. In the reverse direction, right to left, the sweep is known as the "FRO" scan. Timing commences when the TO scan beam passes the receiver and ends when the FRO scan beam passes the receiver. An aircraft to the right of the runway centerline will receive a long time interval when compared to another flying to the left of the centerline. Figure 1 illustrates the concept of the azimuth TO-FRO sweep.

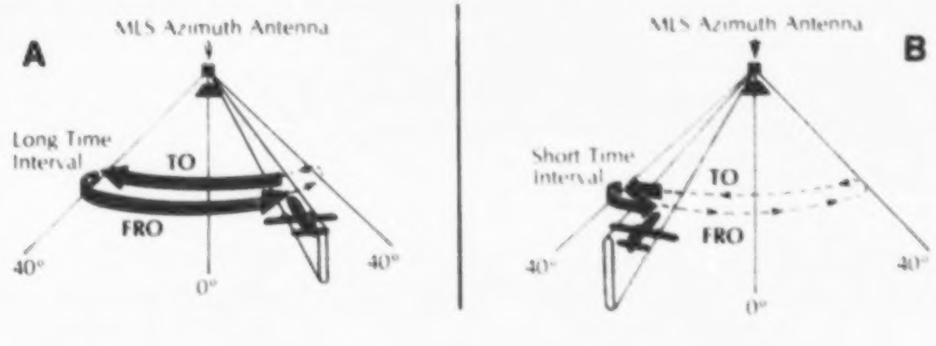


Figure 1 MLS Azimuth Antenna Operation

The time measurement is decoded by the MLS receiver to determine the aircraft's approach angle with respect to the runway. This course is compared with the desired course, selected by the pilot, to give him fly right/fly left information. A pilot can select any approach angle inside the coverage area allowing him to make curved approaches or conventional "straight-in" approaches. MLS which operates on this time difference method is referred to as a Time Referenced Scanning Beam (TRSB) system.

2. ANTENNA SYSTEM DESIGN

2.1 System Requirements

The MLS azimuth Antenna subsystem radiates a narrow fan shaped beam which is scanned "TO" and "FRO" in the azimuth plane.

The general design specifications of the azimuth antenna are as follows:

Frequency Range (Bandwidth)	5030-5090 MHz
Maximum Scan Angle	±42° azimuth
Beamwidth at 5060 MHz	2.0° in scan plane
Peak Sidelobe Level	-20 dB in scan plane
Array Gain	28 dB
Power Handling	10 watts
Beam Scan Rate	20,000°/sec
Operating Temperature	±65° C

Table 1 MLS Azimuth Antenna Design Specifications

The antenna design must also address these considerations.

1. The antenna must withstand adverse weather conditions without degradation of performance.
2. The system must be highly reliable.
3. The system must be cost effective.
4. The system must be easily maintainable by the appropriate personnel.

2.2 Functional Description

Micronav determined that a phased array antenna system will best satisfy the requirements of the MLS. A functional description of each antenna component is given below.

a. Microwave Source

Microwave energy is supplied to the antenna system by the Microwave Source. It consists of a power amplifier, exciter, DPSK modulator and four-way switch providing 10 watts of RF power on the selected channel in the MLS frequency range.

b. Corporate Feed

The corporate feed divides the signal input from the Microwave Source into 54 outputs corresponding to each radiating element of the antenna array. To obtain the desired radiation pattern the signal is divided such that a specific amplitude distribution with equal phase outputs is produced.

c. Phase Shifters

The phase shifters permit independant phase control of each corporate feed signal output. Placed between the corporate feed and the radiating elements, the phase shifters allow the antenna beam to be pointed to the desired azimuth scan angle.

d. Radiating Elements

The radiating elements consist of 54 vertically mounted, slotted antennas. Each element provides a shaped radiation pattern in the elevation plane and a broad pattern in the azimuth plane. These radiation patterns produce a narrow 2 degree wide beam when summed together.

e. Monitor

The monitor, which is a horizontally mounted waveguide, receives an output from each of the 54 radiating elements. The 54 outputs are added together to give a composite signal which is analyzed for faults.

f. I.D. Antenna

The I.D. antenna transmits the DPSK modulated data. This provides specific site information required by the MLS receiver on board the aircraft.

g. Control Electronics

The control electronics consists of the electronic circuitry which generates all the timing and data signals and controls the phase shifters throughout a scan.

A block diagram of the system components is provided in Figure (2).

2.3 Microwave Source

The microwave source energizes the radiating elements by providing 10 watts CW to the phase shifters via the power divider or corporate feed. The main components of the source are a Fujitsu Microelectronics GaS FET Power Amplifier and a Frequency West exciter. The excitor generates a specific frequency which is controlled by its internal crystal. The required stability must be limited to ± 10 KHz maximum. Testing over a 2 hour period demonstrated it to be 150 Hz while maintained at room temperature. To protect the output of the excitor an isolator is used. It prohibits any malfunction, short, or open circuit from damaging the excitor.

A phase shifter is used to modulate DPSK data for the I.D. antenna. It is only used during the period of time that the I.D. antenna is operating. A switch then follows which is shut off during non-transmission preventing microwave leakage to the amplifier. The amplifier has an internal isolator which eliminates the need for an external one as used for the excitor. A four-way switch is fed by the amplifier providing power to any one of the outputs. Only two outputs are used at this time, one for the azimuth phased array antenna and the other for the I.D. antenna. The remaining two, which are now loaded are available for out-of-coverage indicator antennas.

Signals for the microwave switches and the data for the DPSK modulator are provided by the control electronics.

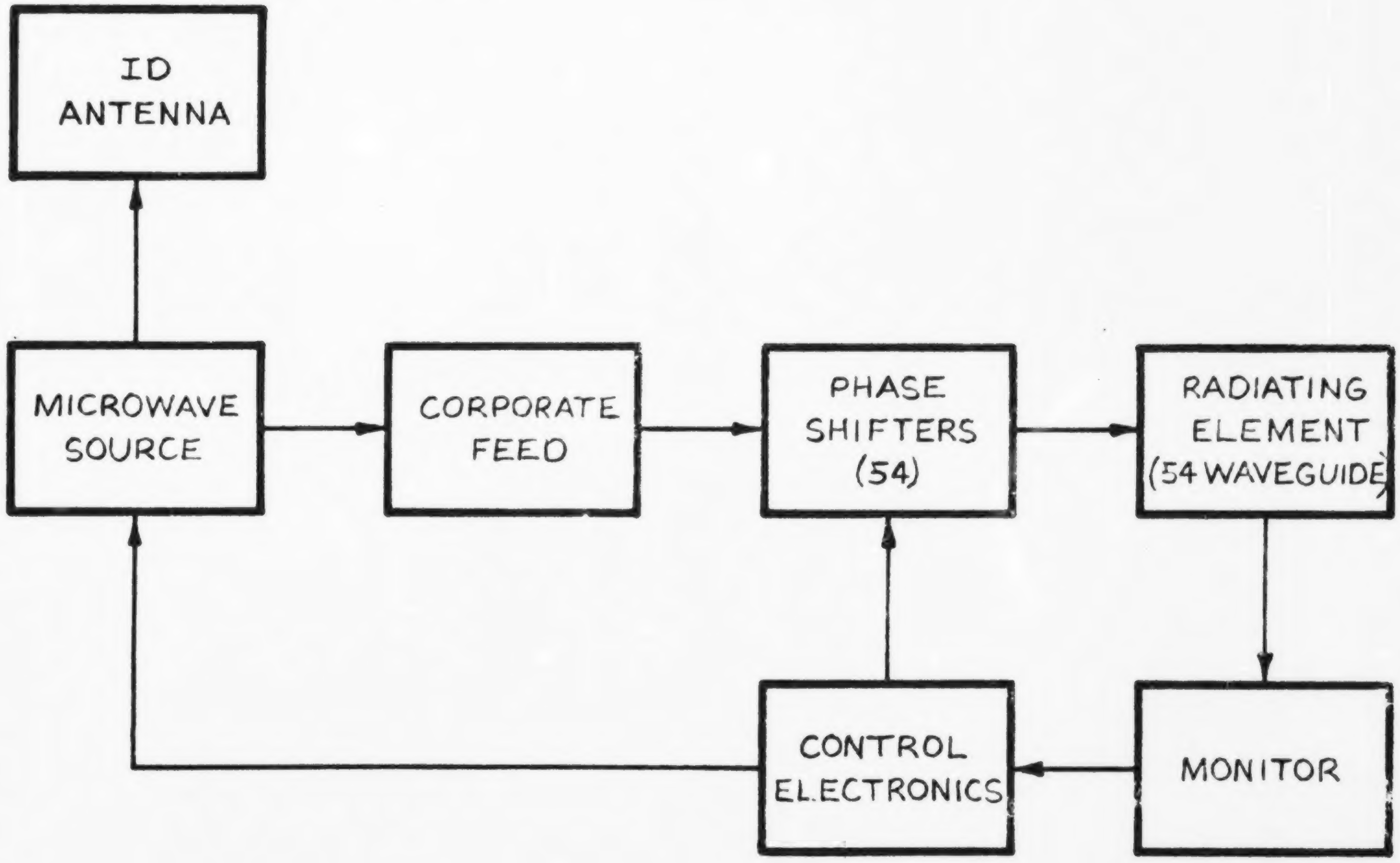

ID ANTENNA
MICROWAVE SOURCE
CORPORATE FEED
PHASE SHIFTERS (54)
RADIATING ELEMENT (54 WAVEGUIDE)
MONITOR
CONTROL ELECTRONICS

Figure 2 System Block Diagram

2.4 Corporate Feed

The corporate feed must divide the input power from the microwave source into 54 outputs according to a Taylor N=4, 30 dB amplitude distribution.

A parallel configuration was chosen for the corporate feed due to its inherent symetry and equal RF path lengths between input and outputs. Modified split-tee dividers were used as power splitters. A split-tee divider is a simple compact device providing two isolated, equal phase, unequal amplitude outputs with a good match at each port. Input VSWR of the split-tee was improved by using a two-step transformer at the input. Power division ratios necessary to accomplish the Taylor distribution were achieved by modifying the impedance of different transmission lines in the individual split-tee power dividers.

The disign was implemented using microstrip circuitry to avoid the cost and complexity at coaxial or waveguide feeds. The physical size of the corporate feed circuitry required that the circuit pattern be deposited on two sheets of the glass impregnated teflon substrate.

Considerable trimming of the microstrip circuitry was required to achieve desirable corporate feed performance. Further iterations of the feed design would concentrate on weight reduction and improved performance.

2.5 Phase Shifter

The phase shifter must delay the output signal relative to its input in discret steps from 0 to 360° of phase. Micronav determined 4 bit phase shifters with a minimum phase increment of 22.5° to be optimal.

Phase shifting may be accomplished using PIN diode or ferrite methods. Pin diodes were selected due to their reciprocity, high switching speeds and microstrip circuitry compatability. A reflection type hybrid circuit configuration was chosen to implement each phase shift bit because it uses only two diodes per bit, can be designed for any phase shift, and requires just one control line per bit.

The phase shifters are constructed on Duriod substrate using a sputtering technique to deposit copper patterns with exacting line definition. Stubs incorporated in the phase shifter design were trimmed to adjust each bit phase and the absolute phase of the device. Trimming the phase shifters to identical absolute phase permits phase shifter interchangability and thus simplified maintenance.

Phase shifter testing demonstrated an RMS phase error of 2 degrees exceeding the original 4 degree requirement. This improvement over the original specification was obtained by careful attention to phase shifter tolerances. The delta insertion loss figures were slightly higher than desired but are offset by this reduction in RMS phase error.

To reduce costs and gain increased performance the phase shifter may benefit from design improvements in the following areas:

1. Simplified production using a conductor backed substrate.
2. Definition of the circuit pattern on the substrate using low cost wet etch techniques.
3. Reduced trimming of stub lines for phase tuning using a refined design.
4. Improved mechanical design for reduced manufacturing costs.

2.6 The Phased Array

The elements of the phased array radiate the narrow beam required. Slotted waveguide radiators were selected for the array because they are compact, rugged, of low insertion loss and low temperature sensitivity. The position, angle and number of slots determines the radiation pattern of the particular slotted waveguide element for a specific phase amplitude and frequency input. The radiating elements were designed using the method of resonant edgewall slots with nonuniform slot spacing. Using this method phase is dependant on slot spacing and amplitude is dependant on slot angle.

The azimuth radiation pattern requirements were satisfied using a Taylor design which yields a theoretical pattern providing optimum compromise between beamwidth and sidelobe level. To achieve a 30 dB design sidelobe level requires 54 radiating elements spaced 3.609 cm apart. A Woodward antenna pattern synthesis was used to shape the beam in the elevation plane.

Slots were cut into WR187 aluminum waveguide tubing using a numerically controlled milling machine. The waveguide receives microwave energy from the phase shifters via identical semi-rigid cable assemblies and a waveguide launcher section. The waveguides were terminated using a specially constructed termination load located in the base of the waveguide. Tuning screws were incorporated in the waveguide design for matching and for absolute phase adjustment so that the radiating elements can be interchangeable.

An integral monitor is used to sample the transmitted signal which is analyzed to check for faults in system operation. The monitor consists of a section of waveguide placed horizontally at the base of the phased array. The array element walls are cut out near the bottom of each waveguide to allow the monitor to fit flush with the interior waveguide surface. This permits microwave energy to be coupled into slots cut in the monitor waveguide. The slots are designed so that an equal amount of energy is coupled into the monitor from each element in the array.

3. TESTING AND RESULTS

Antenna testing was conducted on the Communication Research Centre David Florida Laboratory (DFL) test range near Ottawa. Radiation patterns were plotted to verify antenna performance. Further testing consisted of ground tests at both Micronav and the Sydney airport.

Ministry of Transport flight testing was initiated but not completed due to aircraft equipment difficulties however a portion of the flight checks were flown and MOT repeated Micronav's ground testing. Flight tests should be completed within the month and a copy of the data will be provided to Micronav.

Extensive ground testing revealed that the Micronav MLS azimuth system met or exceeded the requirements of ICAO ANNEX 10 and Standards and Recommended Practices. for signals in space.

The MLS azimuth antenna performed reasonally well in al areas. The major deviation from predicted performance was the increased sidelobe level. The beamwidth and beamshape of the radiation patterns were measured and found correct. Pointing accuracy in azimuth angle was as accurate as could be measured.

Individual system components could be improved in a variety of ways to yield better results. This would typically allow for a relaxation of production tolerance and reduce trimming and adjustment procedures providing a lower cost final product.

4. CONCLUSIONS

An MLS azimuth antenna system has been designed, built and successfully demonstrated to meet or exceed ICAO ANNEX 10 standards. The system is operational and has provided excellent results during ground and flight testing relative to existing MLS designs. Detailed analysis of overall antenna performance justifies the modification of initial design parameters required to achieve a realistic final design.

Future MLS azimuth antenna work is required to "production design" the various components of the system. Improvements in the areas of weight reduction, size reduction and sidelobe level supression are desireable however they will have minimal effect on system performance from a user's vantage point.

BIBLIOGRAPHY

Balonis, C.A. "Antenna Theory, Analysis and Design"
Harper and Row
1982

Canadian Astronautics Limited "Report on a Microwave Lnading System Antenna"
November 1983

Canadian Astronautics Liminted "Report on Phase II Microwave Landing System Antenna"
March 1983

Canadian Astronautics Limited "The Final Report For An Azimuth Microwave Landing System"
February 1984

Edwards, T.C. "Foundations For Microstrip Circuit Design"
John Wiley and Sons
1981

Federal Aviation Administration "Microwave Landing System Ground Equipment" FAA-E-2721/ 1a, 2a, 3b. 4a, 5a
October 1983

Federal Aviation Administration "Microwave Landing System (MLS) Interoperability and Performance Requirements"
FAA-STD-022b
October 1983

Hughes Aircraft Company "Antenna Conceptual Design Study"
May 1981

Interntional Civil Aviation Organization "Aeronautical Telecommunications"
July 1972

Porad, L.I. and Moynihan R.L. "Split-Tee Power Divider"
IEEE Transactions on Microwave Theory and Techniques
September 1964

White, J.F. "Diode Phase Shifters For Array Antennas"
IEEE Transactions on Microwave Theory and Techniques
February 1974

POOR
QUALITY
ORIGINAL